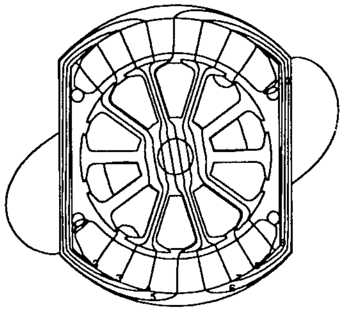

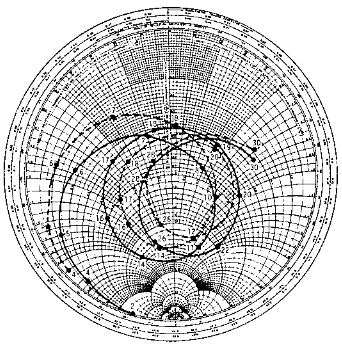

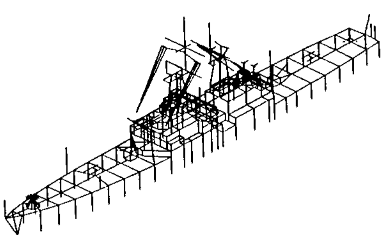

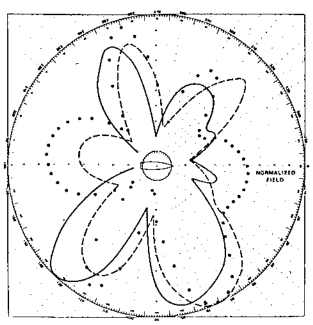

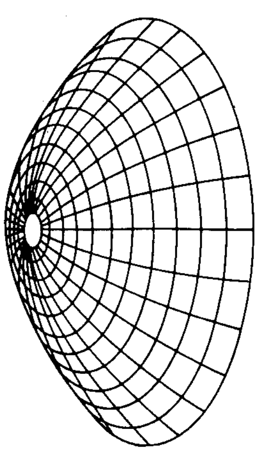

APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY JOURNAL

SPECIAL ISSUE on COMPUTER APPLICATIONS IN ELECTROMAGNETICS EDUCATION

GUEST EDITOR
MAGDY ISKANDER

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GENERAL PURPOSE AND SCOPE. The Applied Computational Electromagnetics Society Journal hereinafter known as the ACES Journal is devoted to the exchange of information in computational electromagnetics, to the advancement of the state-of-the-art, and to the promotion of related technical activities. A primary objective of the information exchange is the elimination of the need to "re-invent the wheel" to solve a previously-solved computational problem in electrical engineering, physics, or related fields of study. The technical activities promoted by this publication include code validation, performance analysis, and input/output standardization; code or technique optimization and error minimization; innovations in solution technique or in data input/output; identification of new applications for electromagnetics modeling codes and techniques; integration of computational electromagnetics techniques with new computer architectures; and correlation of computational parameters with physical mechanisms.

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THE APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY JOURNAL

SPECIAL ISSUE ON ELECTROMAGNETIC EDUCATION

SPECIAL GUEST EDITOR

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REVIEWERS

THE APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY JOURNAL

THE APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY

SPECIAL ISSUE OF THE JOURNAL ON ELECTROMAGNETIC EDUCATION

Vol. 8 No. 1 1993

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EDITORIAL

M. F. Iskander, Guest Editor

I am very pleased to welcome you to this special issue of the *ACES Journal* on electromagnetic (EM) education. This issue emphasizes the use of computers and software tools in EM education. Authors from across the world -- United Kingdom, Canada, France, Romania, Cameroun, and the United States -- contributed to this issue, and it is expected that this joint international effort will have a lasting impact on the development of a computer-based curriculum in EM education. We are grateful to the ACES organization for providing us with this opportunity for sharing our activities, expressing our concerns, and celebrating our successes in this crucial era of computer-based education.

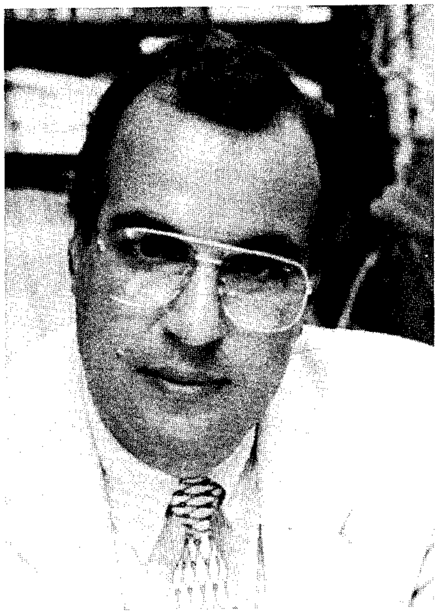
With the proliferation of computers on university campuses and the availability of high-quality software for EM education, computers have become an integral part of modern curriculum development. Visualization capabilities, the ability to simulate laboratory experiments, and one-on-one self-paced tutoring are among the most-often-cited advantages of using computers and software in education. Many of the papers presented in this special issue deal with the development and/or the use of computer software in EM education.

As educators continue to integrate computers in classroom teaching, however, they are beginning to realize the limitations of this technology. For example, it is not clear if students would understand physical principles underlying results from computer simulation and graphical outputs. Even the role of instructors in this new era of computer-based curricula needs to be redefined to maximize benefits to students. Therefore, in addition to developing software for education, some efforts need to be focused on the development of effective means for integrating computers and software in teaching. In this issue are examples of multimedia lessons which combine information from multimedia sources such as software, video, and animated graphics with multimedia instruction including tutorials and quizzes. I truly hope that you will find this issue informative, motivating, and useful in guiding your efforts in developing an exciting EM curriculum at your institution. Equally important, I hope that this issue will increase awareness of the issues involved and stimulate new ideas and sustain our continued search for an effective and exciting means for developing effective means for integration computers and software tools in EM education.

Acknowledgment

I am grateful to Mrs. Holly Cox for her considerable efforts in preparing and handling the many administrative details regarding this special issue. The professional efforts by Mr. Tom Reed in preparing the multimedia lessons is greatly appreciated. The continuous support and capable guidance of David Stein and Stan Kubina are also very much appreciated.

Magdy F. Iskander
CAEME Director



Magdy F. Iskander joined the University of Utah in 1977 where he is currently Professor of Electrical Engineering. In 1981, he received the University of Utah President David P. Gardner Faculty Fellow Award and spent the academic quarter on leave as a Visiting Associate Professor at Polytechnic University of New York. He spent the 1985 and 1986 summers at Chevron Oil Field Research Company, La Habra, California, as a Visiting Scientist. From September 1986 to May 1987 he spent a sabbatical leave at UCLA where he worked on the coupling characteristics of microwave integrated circuits to inhomogeneous media, and at the Harvey Mudd College where he learned about their engineering clinic program. He spent the last four months of the sabbatical leave with Ecole Superieure d'Electricite, Gif-Sur-Yvette, France, where he worked on microwave imaging. His present fields of interest include the use of numerical techniques in electromagnetics.

Dr. Iskander edited two special issues of the *Journal of Microwave Power*, one on "Electromagnetics and Energy Applications," March 1983, and the other on "Electromagnetic Techniques in Medical Diagnosis and Imaging," September 1983. He authored one book on *Electromagnetic Fields and Waves*, published by Prentice Hall, 1992; he edited the *CAEME Software Book*, Vol. I, 1991; and coedited two books on *Microwave Processing of Materials*, one published by the Materials Research Society in 1991 and the second was published by MRS in 1992. The holder of seven patents, he has contributed 16 chapters to 8 research books, published more than 100 papers in technical journals, and made numerous presentations in technical conferences. In 1983, he received the College of Engineering Outstanding Teaching Award and the College Patent Award for creative, innovative, and practical invention. In 1984, he was selected by the Utah Section of the IEEE as the Engineer of the Year. In 1984 he received the Outstanding Paper Award from the International Microwave Power Institute, and in 1985 he received the Curtis W. McGraw ASEE National Research Award for outstanding early achievements by a university faculty. In 1991 he received the ASEE George Westinghouse National Award for innovation in Engineering Education. He also received the 1992 Richard R. Stoddard Award from the IEEE EMC Society. In 1986 Dr. Iskander established the Engineering Clinic Program in the College of Engineering at the University of Utah. Since then the program has attracted more than 45 research projects from 18 different companies throughout the United States. He is also the director of the NSF/IEEE Center for Computer Applications in Electromagnetics Education (CAEME). He coorganized symposia on "Microwave Processing of Materials," held in conjunction with Materials Research Society meetings, spring of 1990 and 1992, in San Francisco. He also organized several workshops and special sessions in conjunction with IEEE symposia. Dr. Iskander is the editor of the journal *Computer Applications in Engineering Education*, published by John Wiley & Sons, Inc. He is a member of the National Research Council Committee on Microwave Processing of Materials and is also a Fellow of the IEEE.

AN ASSESSMENT OF MININEC AND ITS USE IN THE TEACHING OF ANTENNA THEORY

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ABSTRACT

MININEC is a compact, Method of Moments code, written specifically for the personal computer which has evolved considerably in the last decade. This paper presents an assessment of the program and discusses its use in the teaching of antenna theory to undergraduates. The results of a number of validation exercises on the code are included and the simulation of loaded wire antennas, using MININEC, is discussed.

1. INTRODUCTION

Computational Electromagnetics (CEM) has made enormous progress in the last decade. Whereas the use of mainframe and even super-computers is now common-place for the solution of very large problems in reasonable periods of time [1] the application of such techniques as the Method of Moments (MM) on the ubiquitous personal computer has not lagged behind. This has been made possible in the field of wire antenna analysis by the availability and subsequent development of the MININEC software [2]. Described by its originators as a compact code suitable for use on a microcomputer and applicable to small problems, MININEC has now established itself as an extremely useful adjunct in the teaching of antenna theory and as a research tool in its own right.

MININEC, when first made available in 1982 and for some while thereafter, was viewed by many electromagneticists as something of a novelty not to be taken too seriously and certainly not to be trusted. A probable reason for these views was the fact that its public domain status meant that it proliferated through sections of the antenna community (both professional and radio amateur) at such a rate that the excellent documentation supplied by its originators [2] was often lost on the way! The code was frequently misused and its capabilities and limitations certainly misunderstood. It is the intention in this paper to review the MININEC program in its evolutionary forms; to provide some examples to validate its performance and to show how it has been used most effectively in the undergraduate teaching environment.

2. BACKGROUND

MININEC was written in the BASIC language and uses a modified Galerkin procedure to solve the electric field integral equation (EFIE) for the current distribution along a thin-wire, or series of suitably interconnected such wires for given source and loading configurations. Being compact, the original MININEC ran to only 550 lines of code and fitted within the 64 kilobyte memory capability of the pre-"pc" era of microcomputers. As such, it was only capable of handling 40 unknowns [2] and this set the original limit as regards the number of wires used, their segmentation and the number of discrete sources and loads which could be accommodated. Subsequently, up to 10 wires, divided into a total of 70 segments, could be handled with the resulting structure being either in free space or above an infinite, perfect ground plane.

Various extensions, modifications and up-grades to MININEC followed rapidly [3-6], mainly from the code's originators but also from others [4], who added a graphics capability for displaying the geometry of the modelled structure as well as radiation patterns and input impedance plots on a Smith

chart. The fundamental limitation on the size of problem that could be handled is the BASIC compiler common to personal computers and this set 100 unknowns as the typical upper limit. However recently available compilers have allowed this limit to increase to about 200 unknowns in version 3, with the principle limitation now being set by the size of the CPU [7]. The latest versions of MININEC [6], of which two more, MN and ELNEC, have appeared most recently within the amateur radio literature [8], are available as sophisticated, well-structured and user-friendly programs which are based on MININEC version 3. As such, they represent a significant advance over their predecessors by incorporating excellent graphics with the capability of viewing the geometrical configurations in three dimensions and, in some cases even allowing them to be rotated for viewing from any angle. Antenna currents can be plotted on the wires in magnitude and phase formats and far-field azimuth and elevation patterns in polar or rectangular coordinates. In addition, the patterns produced by two antennas can be compared easily at a keystroke.

Validation of the computed results produced by any analytical software is obligatory before the code can be used with confidence. More will be said about this later but, at this stage, it should be made clear what the essential differences are between MININEC and NEC, the Moment Method code from which it was originally derived. NEC, [9], with its version 3 the most recently available, has become regarded as the virtual industry-standard for the analysis of so-called low-frequency antennas [10]. Computed results obtained from NEC are therefore used frequently as the standard against which those obtained from other techniques, such as MININEC, are judged. This may seem strange given the apparent lineal descendancy of MININEC from NEC. However there are significant differences between them. Firstly, NEC solves the EFIE or the magnetic field integral equation (MFIE) by using either wire elements or surface patches to configure the geometry in question. MININEC

is based on the numerical solution of the EFIE using thin wire elements. Both codes of course use the Method of Moments to do this but NEC uses a three-term (constant, sine and cosine) form as the current basis function with a delta function as the weighting function. By contrast, MININEC uses the Galerkin procedure, with pulse basis and testing functions and this, for some applications, has real advantages because of the resulting symmetrical impedance matrix [11, 12]. Essentially therefore MININEC and NEC are different formulations and it is therefore valid to use the results from one to check or confirm those from the other, assuming appropriate use of each for the problem in hand.

From here on only the most recent versions of MININEC [5-8] will be considered. These now offer the capability of computing both near and far-fields and also include real ground as well as free space and perfect ground planes. However, unlike NEC, only far-field characteristics are computed over real ground. The current distribution and driving point impedance are determined over perfect ground. This can lead to erroneous results with certain antenna configurations particularly if they are close-to or fed against ground. Up to ten concentric ground zones may be specified [8] or up to five zones with linear boundaries [5]. The conductivity and relative permittivity of each zone are defined by the user and these zones may also be at different heights above the xy (horizontal) plane, thus effectively simulating the topography of the land. The first zone can also accommodate a radial wire ground screen. Again, there are differences between how MININEC and NEC handle these far field cases. MININEC uses the Fresnel reflection coefficient method whereas NEC also has the capability of using the considerably more complex and more realistic Sommerfeld integral method for computing the effects of ground reflections as well as for determining the driving-point impedance over real ground as well as for wires both very close to and even penetrating the air-ground interface.

The choice of segmentation schemes is a key aspect for the successful use of both NEC and MININEC. The various versions of the MININEC documentation [2, 5, 6] contained detailed information on the most appropriate segmentation schemes for antennas and structures which were either electrically short, resonant or anti-resonant. Adherence to these recommendations generally produced accurate results for simple antennas which contained straight elements and which did not require the inclusion of imbedded transmission lines, such as the log periodic dipole array (LPDA). However, junctions between wires with significantly different lengths could produce completely erroneous results unless careful attention was paid to the ratio of segment lengths on interconnected wires [13]. The use of a tapered segmentation scheme is recommended to overcome this problem since it also minimises the total number of segments used and thereby reduces the run-time. Automatic segmentation routines, which can, if required, be overridden by the user, are now provided in the latest versions of code, such as MN. These also automatically taper the segments in the vicinity of junctions should this be necessary.

Where MININEC is used to model geometries containing bent wires such that the included angle between wires is less than 180 degrees, then errors can result unless suitable precautions are taken. These errors occur as frequency offsets, with the computed results being displaced upwards in frequency by as much as 3 or 4 per cent when compared with those generated by NEC. This frequency offset effect also occurs when the radius of the elements is increased. Thus thick or fat structures must be modelled with care unless the code used has a built-in correction for these effects. The MN version of the code, due to Beezley [8], does contain improved algorithms which correct for all these offsets due to either the use of thick wires, the geometric distortion at bent-wire junctions and for discontinuities in segment lengths.

3. VALIDATION OF MININEC

Regardless of its application and its degree of sophistication a piece of simulation software is of no value whatsoever if the results it produces are incorrect. This is equally true whether the program is used in research, development or in the educational process. MININEC therefore has been subjected to considerable assessment over the years in order to validate the results for a variety of antenna configurations [8, 14]. Some of these, from this latter validation exercise, will be discussed here.

a) Input impedance of a halfwave dipole

It is recognized [15] that the input impedance of an antenna is the parameter most sensitive to computational error because of its critical dependence on the current distribution. In addition the specific geometrical details of the feed region are especially important in determining input impedance. Whereas NEC allows for a variety of different source schemes, MININEC only accommodates a simple voltage source at specified points on a wire. The most recent versions of the code also allow current sources to be used. Other than the segment tapering discussed above no special geometrical factors are considered in the feed region. Figure 1 shows computed values of the input impedance of a dipole antenna of length 2 h = 0.5 m, radius, a = 0.001 m at 300 MHz. Results for this geometry are shown using MININEC, NEC version 2, a code due to Richmond [16] and, from a Galerkin-based code with a tapered segmentation scheme [17] for five specific feed region geometries. Also plotted (though unrelated to the number of segments) is the result from King and Harrison [18], by way of comparison. Note that both the NEC and Richmond results agree with those of King when about 5 segments per quarter wavelength were used. MININEC required somewhat more, with the reactance being the more critical parameter. The data from [17] seem to converge to those of King, in the real part, for a segment count between those of NEC and MININEC. By contrast, the reactive components from [17]

show no evidence, from the data available, of converging on King's value. One is left to conclude that MININEC computes input impedance at least as accurately as do other well respected procedures but that the true value of the input impedance of the half wave dipole remains an interesting, though as yet, uncertain quantity, particularly when the detailed shape of the feed region is considered.

b) V-dipole antenna

The centre-fed V-dipole antenna illustrates the problem of modelling bent wire antennas. Figure 2 shows the input impedance of such an antenna where $2h = 0.5\lambda$ and of wire radius a, for the case where $h/a = 2 \times 10^4$ [19]. This result was obtained from a Galerkin procedure using sinusoidal expansion and testing functions which agrees with the so-called King-Middleton second order solution [18]. Also shown are the MININEC results, using [6] and those from NEC for the input impedance. The real part, as given by both codes, is in excellent agreement for all values of the included angle θ whereas the MININEC imaginary part deviates markedly as θ is decreased. Doubling the number of segments per wire from 10 to 20 produced no change in the real part in either code and only corrected the imaginary component from MININEC by about 20 percent when the included angle was 30 degrees. By contrast the NEC2 results agree very well with those of Jones [19]. However if a tapered segmentation scheme is used in the vicinity of the source then the MININEC results are indistinguishable when plotted with those computed with NEC.

c) Yagi-Uda array

This antenna, which dominates most of our skylines, has been subjected to considerable analysis, measurement and optimization. A two element array, from [20] was used as the basis for comparison of computed results of input impedance, gain and front-to-back ratio. The array consisted of a driven element of length 0.470λ and a reflector of 0.494λ, spaced 0.141λ apart

and both elements were untapered with radii of 0.0006 λ. Good agreement was found between results from [20], those using MININEC [6] and a moment method code developed by Pozar [21] specifically for modelling simple Yagi arrays. Only the front-to-back ratio is shown here in Figure 3 because it illustrates the degree of agreement between three very different computational techniques for determining a parameter which is particularly sensitive to the current distribution on the array. Lawson assumed it to be sinusoidal while Pozar used a piece-wise sinusoidal expansion function in a Galerkin procedure. Both agree well with the MININEC result at the F/B peak and continue to do so across the frequency range. The sinusoidal distribution produces excellent agreement at the peak but some deviation at the other frequencies. Frequently, the experimental results obtained by Viezbicke [22] are quoted as the standard reference when assessing the Yagi-Uda antenna. Figure 4 shows the effect on gain of changing the spacing between the 0.482 λ elements of a two element array where the parasitic is a reflector. Whereas the data from MININEC, NEC, Lawson and Pozar are in close agreement, those of Viezbicke deviate markedly and indicate very little dependence on spacing. This conflicts with practical experience and with the results of an detailed analysis [24] of this antenna.

d) Loaded short monopole

Hansen [23] has shown how the radiation efficiency of an inductively loaded short monopole varies with the position of the appropriate inductor required to produce resonance. Since all versions of MININEC allow the inclusion of lumped RLC loads within a structure, at defined segments, the antenna in Figure 5 was modelled. Here h = 1 m and Q_L is the quality factor of the inductor. There is excellent agreement between Hansen's results and those from MININEC. It was this ability of the code to accurately predict such characteristics for antennas of this type which led to the development of a simulation exercise for use by undergraduates which will be described

next.

Numerous other validation exercises have been performed [14] to assess the accuracy of the results predicted by MININEC. As indicated here it was found that the code produces entirely acceptable results for a variety of wire antenna configurations, both single-element and arrays, and when loaded with lumped components.

4. A TEACHING EXERCISE

The difficulty of mounting meaningful antenna experiments in a teaching laboratory environment, other than for demonstration purposes, is well known. Prior to the availability of readily accessible, user-friendly computer programs like MININEC (particularly in its most recent versions), courses on antennas tended to be entirely theoretical with occasional use being made of a microwave test-bench to examine characteristics like the radiation patterns of a rather limited number of antennas.

Whereas such practical experience is still to be encouraged there is now considerable scope to go well beyond what is possible in that rather limited situation. A computer modelling exercise using MININEC version 3 will now be described. It has been run very successfully since 1986 at the Universities of the Witwatersrand, in Johannesburg, and Liverpool [25].

a) A thin-wire short dipole

The characteristics of a thin-wire, short dipole ($2\ h \ll \lambda$) in free space are readily calculable using some fairly simple, through appropriate, approximations. It is assumed that the current distribution along the centre-fed antenna is triangular by choosing its length, $2\ h < \lambda/4$. Therefore, on this basis, the radiation resistance may be written as:

$$R_{rad} = 20\ \pi^2 \left(\frac{2h}{\lambda}\right)^2 \qquad (1)$$

while its input reactance can be obtained approximately by treating the antenna as an opened out, open-circuit transmission line, if one assumes that this cylindrical antenna is the limiting case of a biconical antenna with cone half-angle θ. Incidentally, as Collin [26] points out, the current on such an infinitely thin cone becomes a pure sinusoidal standing wave, which provides the basis for the well-used assumption of a sinusoidal current distribution on thin-wire antennas. Based on Collin's approach we proceed as follows:-

The characteristic impedance of the biconical structure is given by:

$$Z_o = 120 \ln \cot \frac{\theta}{2} \tag{2}$$

Now, the cylindrical antenna in Figure 6 is equivalent to a transmission line whose characteristic impedance varies gradually along its length. For θ small we have that $\tan \theta = a/x \simeq \theta$, therefore:

$$\cot \frac{\theta}{2} \simeq 2/\theta = 2x/a \tag{3}$$

Hence the characteristic impedance of the thin cylindrical antenna at the point x is:

$$Z_o(x) \simeq 120 \ln \frac{2x}{a} \tag{4}$$

and so, to a first approximation, the average value of Z_o for an antenna of length 2 h is given by:

$$Z_o = \frac{120}{h} \int_o^h \ln \frac{2x}{a} \, dx = 120 \left(\ln \frac{h}{a} - 1 \right) \tag{5}$$

The input reactance, X_{IN}, of this thin-wire antenna is then obtained from the lossless transmission line model with the load, Z_L, being open-circuit, hence $Z_L \rightarrow \infty$.

$$\text{Thus } X_{IN} = \frac{Z_o \, (Z_L + j \, Z_o \tan kh)}{Z_o + j \, Z_L \tan kh} \tag{6}$$

$$\text{or } X_{IN} = - j \, Z_o \cot kh \tag{7}$$

where $k = 2\pi/\lambda$.

The theoretical input impedance of this short, thin-wire dipole is therefore:

$$Z_{IN} = 20 \, \pi^2 \left(\frac{2 \, h}{\lambda}\right)^2 - j \, Z_o \cot kh \tag{8}$$

where the only losses are assumed to be due to radiation.

For the simulation exercise a centre-fed dipole of length $2 \, h = 5$ m and of radius $a = 2$ mm was used at a frequency of 10 MHz. From (5) $Z_o = 819 \, \Omega$ and therefore, from (8), the input impedance is readily calculated as $Z_{IN} = 5.48 - j1418 \, \Omega$. Whereas the effort in obtaining this result is minimal the learning process is considerably reinforced when the same antenna is analysed using MININEC. Before doing so, two constraints must be satisfied: that $a/\lambda \ll 1$ and that $2 \, h/a \gg 1$. These imply effectively that only axial currents flow on the conductor. Clearly, in this case, both are satisfied. The choice of segmentation scheme is determined by a number of factors, with increased accuracy resulting from an increase in segments, N, into which the wire is divided as long as a further constraint, that $\Delta/a > 10$, is not violated, where Δ is the length of a segment. However, increasing the number of segments also means an increase in computation time and so a sensible choice of N would be based on the recommendations in [2]. Choosing N = 8

produces the computed input impedance $Z_{IN} = 5.48 - j1284\ \Omega$.

The agreement for the resistive components is exact. Thus the postulated triangular current distribution is confirmed and may be plotted, as further evidence, by examining the current distribution pulse-by-pulse in the appropriate MININEC file.

The computed value of input reactance and that from the transmission line model agree to within about 10 percent. This is a reasonable engineering result and indicates the adequacy of the simple transmission line model in this case.

b) An inductively loaded short dipole

By inserting a lumped inductor with $X_L = j1248\ \Omega$ at the feed point the antenna is made to resonate. Realistically, that inductor will have finite Q where

$$Q = 2\pi fL/R \tag{9}$$

with R being the loss resistance of the coil.

Using Q = 100, which is a reasonable value for an air-cored inductor suitable for this application, yields $R = 12.84\ \Omega$ and therefore the input resistance of the antenna rises to $R_{IN} = 5.48 + 12.84 = 18.32\ \Omega$. By inserting this inductive load at the source in the MININEC model the computed input impedance becomes $Z_{IN} = 18.3 - j0.19\ \Omega$; effectively resonant, as intended.

Clearly the loss introduced by this loading inductor decreases the radiation efficiency, η, where

$$\eta = R_{rad}/(R_{rad} + R_{loss}) \tag{10}$$

thus $\eta = \dfrac{5.48}{18.32} \times 100 = 29.9$ percent

In addition, the gain, G, will be reduced because

$$G = \eta D \tag{11}$$

where D is the directivity of the antenna.

A reasonable assumption for the student to make is that the directivity of the unloaded antenna is 1.5 since it is electrically short. The MININEC simulation effectively confirms this by yielding D = 1.79 dBi (1.51). When the antenna is loaded with that inductor, the computed gain is -3.46 dBi (0.45).

Thus $\eta = \dfrac{0.45}{1.51} \times 100 = 29.9$ percent, exactly as calculated above.

Increased radiation efficiency (and hence gain) can be achieved by moving the inductive loading out along the arms of the antenna, as shown previously by Hansen [23]. Again, this case is readily calculable by hand using Collin's [26] transmission line approach and is illustrated in Figure 7.

If two, equal, inductors are moved a distance ℓ from the centre of the antenna and their value adjusted to maintain resonance at the feed point, then it can be shown that the inductance required per arm of the antenna is:

$$L_{\text{per arm}} = \frac{Z_o}{4\pi f}\left(\cot k(h-\ell) - \tan k\ell\right) \qquad (12)$$

This result follows from the transmission line approximation of the antenna where, again, the input reactance at the feed point is given by:

$$X_{IN} = \frac{Z_o\,(X_L' + j\,Z_o \tan k\ell)}{Z_o + j\,X_L' \tan k\ell} \qquad (13)$$

with Z_o from (4) and X_L' is the load on the equivalent transmission line of length ℓ, which consists of two inductors of L/2 in series with an open-circuit transmission line of length $(h-\ell)$.

Thus $X_L' = j\omega L - j\,Z_o \cot k\,(h-\ell)$ (14)

At resonance the numerator of (13) must be zero, therefore:

$$Z_o \; (\cot k \; (h-\ell) \; - \; \tan k\ell) = \omega L \tag{15}$$

from which (12) follows easily since the required inductance per arm is simply L/2.

If these inductors are placed centrally within each arm of the antenna then $\ell = h/2 = 1.25$ m and so, from (12), $L_{per\ arm} = 22.6\ \mu H$ or a lumped reactance of 1419 Ω per arm.

After inserting these inductive reactances (initially with $Q \rightarrow \infty$) at the mid-point of each arm (segments 3 and 9) in the MININEC model the computed input impedance is $Z_{IN} = 15.83 + j454$. Clearly the antenna is not resonant. Some iteration is required as the inductive loads are reduced. After one or two judicious changes to a value of $L_{per\ arm}$ of 19.7 μH resulted in an input impedance of 12.56 + j0.17 which is essentially resonant. It should be noted that the simple transmission line model produced a value for the inductive loads which was about 13 percent lower than that obtained from the simple model. Again, this indicates the usefulness of a simple procedure which is based on a plausible model.

c) Current distribution along the loaded antenna

Considerable insight may be gained into the characteristics of this off-centre loaded antenna by examining its current distribution. Firstly, the effect of the inductors is to maintain the current approximately constant between the feed point and each load; secondly, the boundary condition at the end of each wire requires that the current there is zero and thirdly, because $(h-\ell) << \lambda/4$, the current decays linearly from each inductor to the wire-end. This arguement therefore suggests that the current distribution along this particular loaded antenna will be trapezoidal. Of course MININEC displays the current at each segment and therefore this postulated distribution is easily confirmed and is shown in Figure 8.

It will be noted that the MININEC distribution shows some current peaking at the position of the loads. This effect was discussed by Hansen

[23] and is caused by the fact that the inductance required to force resonance in the antenna is actually slightly larger than that required to maintain the current constant between source and load. The additional inductive element manifests itself by a slight increase in current amplitude at each load. Such agreement between MININEC and the literature is most reassuring, not only to the student!

By effectively causing the current to maintain its value as far as the load, instead of falling linearly to zero, as with the unloaded antenna, the current moment, and with it the radiation resistance, of the antenna have been increased. Current moment is simply related to the area A under the current distribution curve, which in turn is a measure of the field intensity (E or H) produced in the far-field by the antenna. Thus, for the unloaded antenna, with a triangular current distribution with maximum value, I,:

$$A_1 = I\ h \qquad (16)$$

The loaded antenna, with the trapezoidal current distribution of the same peak value, has a current moment of:

$$A_2 = (h \times I) + 2\left(\frac{h}{4} \times I\right) = \frac{3\ h\ I}{2} \qquad (17)$$

Now the power radiated by the antenna is:

$$P \propto \frac{E^2}{Z_i} \propto H^2 Z_i \qquad (18)$$

where $Z_i \approx 120\ \pi\ \Omega$ is the intrinsic impedance of free space. Clearly, therefore, the ratio between the powers radiated by the loaded and unloaded antennas is:-

$$P_2/P_1 = (A_2/A_1)^2 = (3/2)^2 = 2.25 \qquad (19)$$

If the peak feed-point current into each antenna is the same then the increase in radiated power must be due to an increase in radiation resistance

in the loaded antenna compared with that of its unloaded counterpart. Thus:

$$\frac{R_{loaded}}{R_{unloaded}} = 2.25 \tag{20}$$

By comparison, the two values of R_{rad} computed by MININEC for these loaded and unloaded antennas were 12.56 Ω and 5.48 Ω respectively. Their ratio is 2.29 - in excellent agreement with (20).

Finally, the improvement in radiation efficiency which was achieved by displacing the loading from the centre feed-point is readily calculable and checked by using MININEC. Again we use a realistic value of Q = 100 for the loading inductors. From the value of 19.7 μH required for resonance we calculate the loss resistance (ignoring any losses in the actual antenna conductor) as $X_L/Q = 12.38\ \Omega$. However this value is transformed by the section of the antenna between the feed-point and the load such that the real part of the input impedance, as determined by MININEC, is 38.6 Ω. This corresponds to the sum of R_{rad} plus R_{loss}. The radiation resistance alone is found easily, with MININEC, if one assumes that the inductors are lossless (i.e. $Q \to \infty$). Hence, the code yields $R_{IN} = R_{rad} = 12.6\ \Omega$, from which the radiation efficiency follows as $\eta = \dfrac{12.6 \times 100}{38.6} = 32.6$ percent

As was done before the radiation efficiency can also be obtained by computing G and D and then using (11). Thus, with lossless inductors G = D = 1.80 dBi (1.514) while when Q = 100, G = -3.07 dBi (0.493). Therefore the radiation efficiency, from (11) is $\eta = G/D = 32.6$ percent, as expected.

The effect of moving the loading inductors away from the feed-point has increased the radiation efficiency from 29.9 percent to 32.6 percent, which, seemingly, is not too significant. However it should be noted that this change was accompanied by an increase in input resistance from 18 to 39 Ω which eases the impedance matching requirements quite considerably if the

antenna is to be fed with 50 Ω coaxial cable. This inter-relationship between VSWR and radiation efficiency occurs frequently when attempts are made to enhance the performance of simple antennas, usually by some form of loading to increase their VSWR-bandwidth. It therefore emphasises the need to always consider both aspects when evaluating such antennas.

5. CONCLUSIONS

The evolution of MININEC has been reviewed from its release a decade ago as a very simple wire modelling code to its present status where both its capabilities and its usefulness have been enhanced considerably. Its role in the teaching of aspects of antenna theory has been used to illustrate some of its features and various examples were included of validation exercises which were designed to determine the accuracy of the code in predicting the performance of wire antennas.

It is concluded that the most recent versions of MININEC, (version 3 onwards), are accurate and highly versatile codes, which are particularly simple to use. The advanced graphics features now available make them ideal for use in antenna simulation exercises in the teaching environment.

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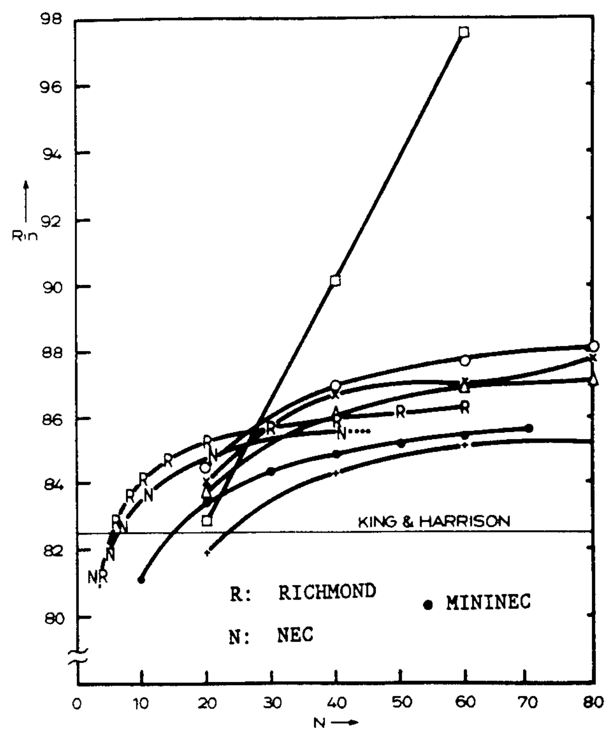

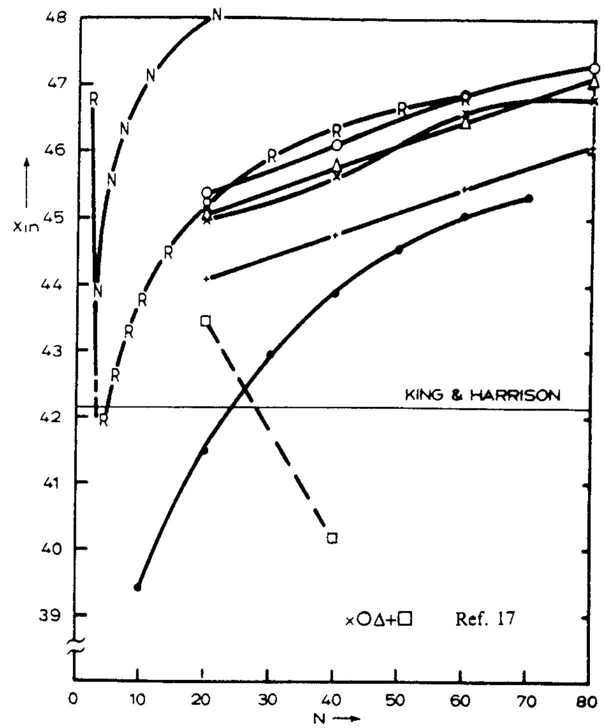

Fig.1. Computed input impedance of the half wave-dipole.
(2h = 0.5m; a = 1mm; f = 300MHz).

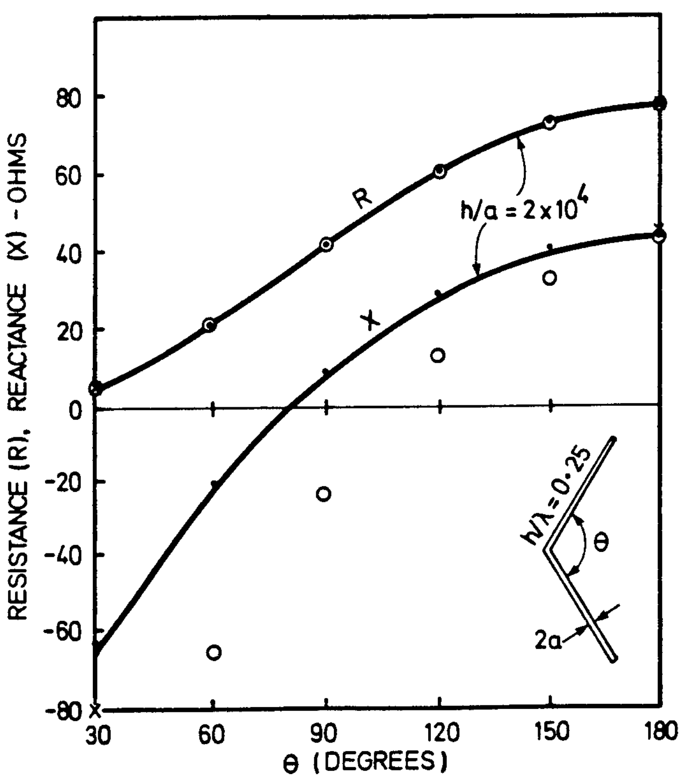

Fig.2. Input impedance of half-wave V antenna;
—— ref.19; O MININEC (no taper); • NEC

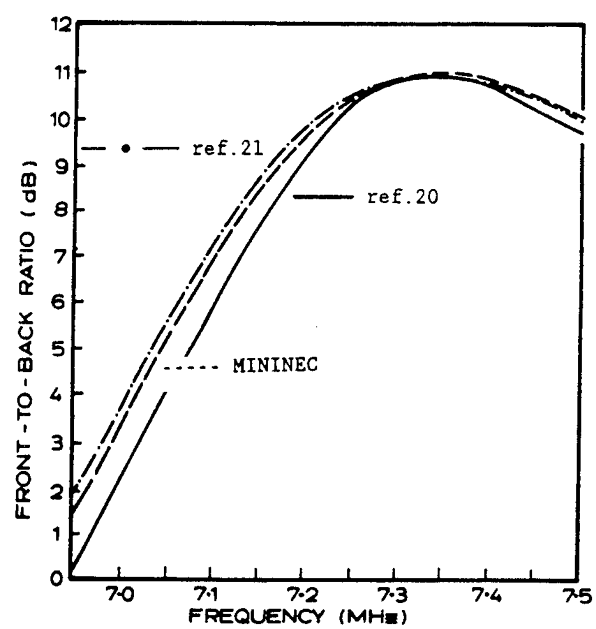

Fig.3. Computed front-to-back ratio of Yagi-Uda array;

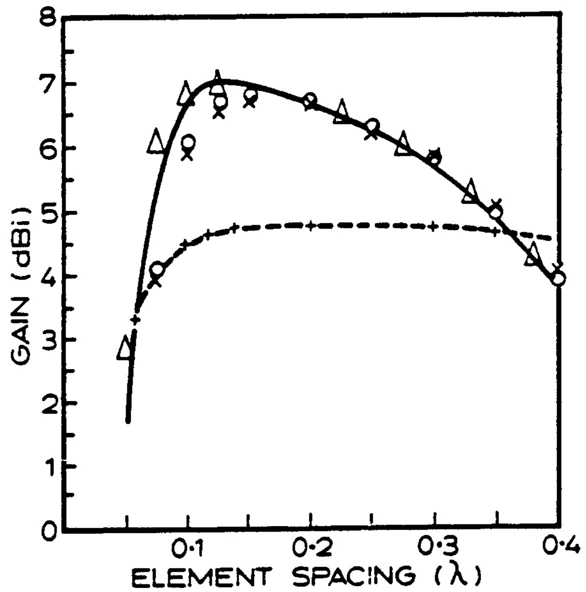

FIG. 4: Computed gain with spacing of the Yagi-Uda array.
—— ref. 20; o MININEC: Δ NEC 2; x ref. 21; —+— ref. 22

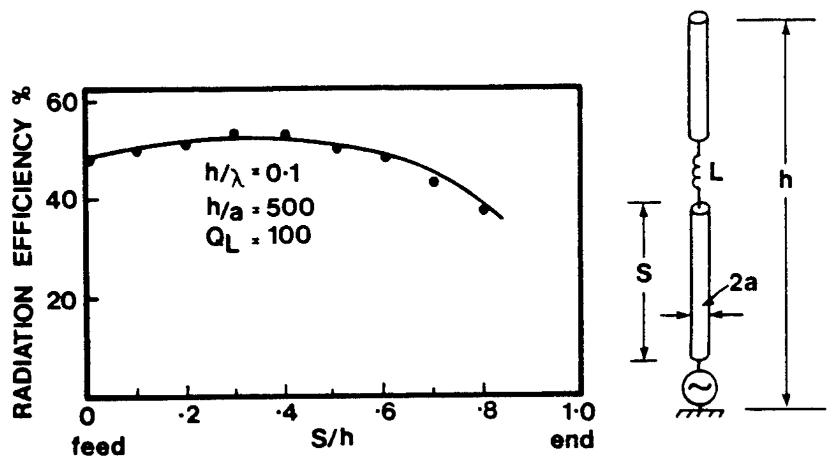

Fig.5. Radiation efficiency of short loaded monopole;
—— ref.23, • MININEC

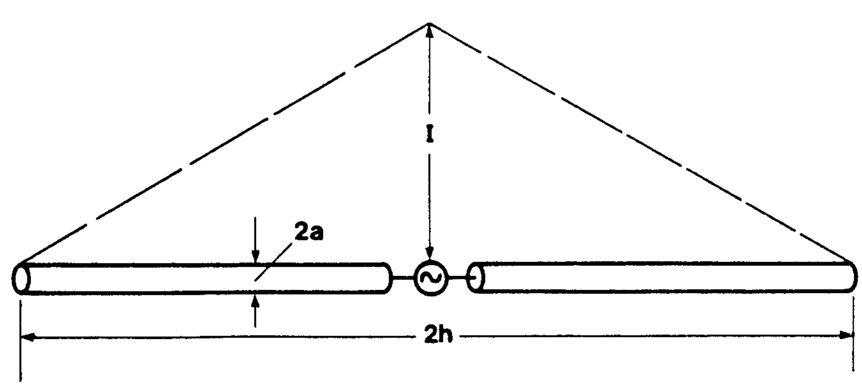

Fig.6. Thin cylindrical antenna.

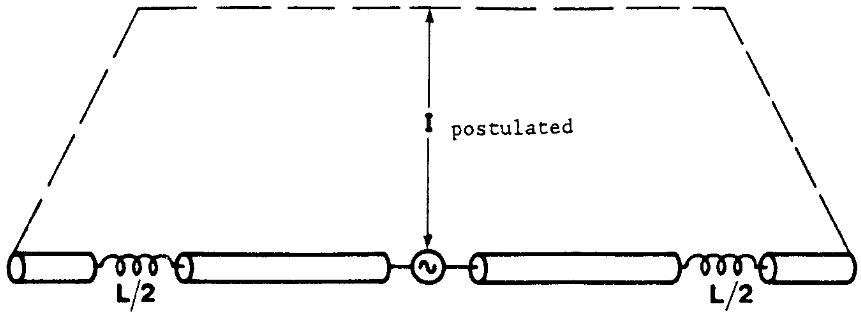

Fig.7. Loaded cylindrical antenna.

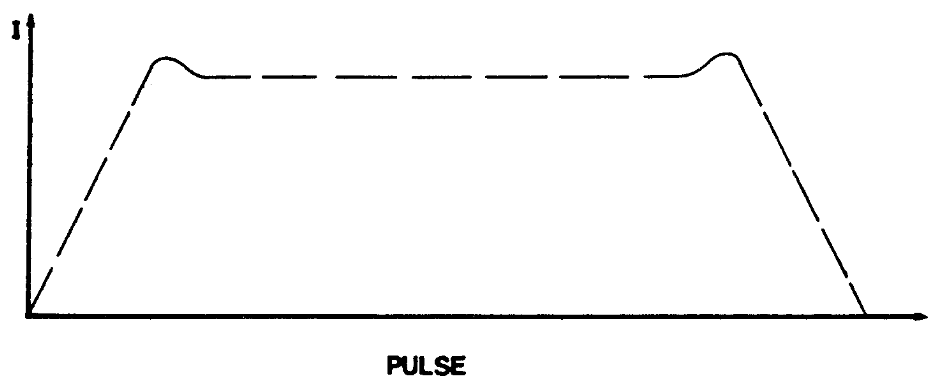

Fig.8. Current distribution: computed.

ELECTROMAGNETIC COMPUTATIONAL METHODS IN THE TEACHING OF ELECTROMAGNETIC COMPATIBILITY

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Abstract

The teaching of Electromagnetic Compatibility (EMC) is gaining acceptance as an important subject that needs to be taught in the Electrical Engineering curriculum at the undergraduate and graduate levels. It has become evident that EMC plays an important part in the design and manufacture of electronic components, subsystems and systems; hence, the need for its teaching. Traditional approaches for the teaching of EMC have focused on analytical methods for the study of diverse types of interference mechanisms. Recently, the use of computational electromagnetic methods in the analysis and solution of EMC problems has been introduced in the teaching of EMC. Students have shown great interest in an EMC course where the use of computer methods helps in their understanding of this, sometimes, difficult subject.

INTRODUCTION

In a regular electrical engineering curriculum at the undergraduate level students are taught the fundamentals which will guide them in the design, analysis, manufacture, and testing of electronic components, devices and systems. At the graduate level a greater "in depth" view is taken of the previously taught subjects. Regardless of the level of instruction (undergraduate vs graduate) most of the teaching in our engineering schools is still done in a sequential manner. For example, a student will not take a course in Antenna Theory until a course(s) in Electromagnetic Theory is part of his/her general knowledge. Not surprisingly most graduate courses have undergraduate courses as pre-requisites. Recently however, an emphasis on "synthesis engineering education" has caught the attention of many educators [1]. In synthesis engineering education, subjects from different fields can be taught simultaneously by making use of commonalities among the subjects themselves; hence, the description of the radiated fields from a radiating dipole (as taught in an antenna course) can be covered as an extension in the treatment of Maxwell's equations.

The subject of Electromagnetic Compatibility (EMC) is slowly gaining acceptance as a topic that could fit the synthesis

engineering education approach that is needed for the solution of real-world Electromagnetic Interference (EMI) problems, which are constantly faced by the electronic industry [2]. Too often however, in the design and manufacture of electronic devices very little attention is focused on the possibility that EMI may occur among susceptible devices. For example, though students are taught the fundamentals of how to design and manufacture many types of electronic devices, the fact that such devices may not function together in the common electromagnetic environment of a system is hardly taught at most engineering schools [3]. EMC, as part of the synthesis engineering approach, should be taught at all stages in design/electronic manufacture engineering courses.

Because EMC/EMI is not properly taught to most engineers, many of our engineering schools are graduating professionals who lack this expertise within the field of electronic design. In industry, this situation often translate to the lack of implementation of comprehensive EMC plans in the design stages of electronic products; hence, EMC is only considered after the design is complete and inherent incompatibilities arise. Because EMC is not "built-in" in the design process, EMI problems are fixed using "band-aid" approaches. The final results are delays in product delivery, degraded performance, and increased costs.

There is a need to educate our future engineers in good design practices which incorporate, among other things, good EMC planning. Incorporating EMC in a synthesis engineering education approach is the best method to accomplish this task. In the last few years several universities in the US and Europe have taken steps to incorporate EMC in their undergraduate electrical engineering curriculum [4-6]. This effort has also been extended to graduate education [7]. The use of Electromagnetic (EM) computational methods has been a valuable tool in the teaching of EMC at the graduate level [7]. The first part of the paper reviews some fundamentals of EMC codes that use analytical methods. The second part of the paper discusses the use of computational electromagnetic methods in the teaching of EMC. Some examples where students can learn to apply EM computational methods for solving EMC problems are discussed. It is assumed that the students already have a basic understanding of EMC which is typically gained from an undergraduate course on the subject.

FUNDAMENTALS OF EMC CODES BASED ON ANALYTICAL METHODS.

Before the advent of digital electronics the general concepts of EMC and EMI referred mostly to Radio Frequency Interference (RFI) effects between transmitters and receivers. The root causes of RFI are the inherited non-linearities existing in transmitter and receiver circuits which could downgrade their performance. Tables

1a and 1b show a list of RFI problems (transmitters and receivers) and how they originate. As an introduction, EMC students are exposed to these RFI concepts with several worked examples. Though some computer codes are used for performing RFI analyses [8-9], they are not discussed in this paper.

The introduction of digital electronics has significantly increased EMI problems in electronic devices creating a marked awareness of the importance of EMC. Digital electronics not only has increased the frequency range of the noise environment (KHz to several GHz), but has also increased the susceptibility of electronic components to that noise environment [10]. Presently, EMC has to address interference issues at the inter-system level (e.g between transmitters and receivers) and at the intra-system level (self-compatibility). There is a pressing need to teach engineering students about good EMC design practices in our digital/analog design courses.

The use of software tools based on analytical methods for the solution of EMI problems focuses on the following principles: a) analytical methods are suitable for teaching at the classroom level, b) analytical methods provide physical and mathematical insights into the theory of EMC for ease of understanding by the students, and c) analytical methods can provide results which are reasonably accurate for topologically simple EMC problems, which in many practical situation are a good approximation to the real EMC situation.

EMC codes which use analytical methods can process large amount of input data and perform a large number of computations. Students are taught however, that the "physics" of the codes is based on several variations of well known analytical expressions for the different types of EMI coupling mechanisms. Several coupling models between noise sources and victim circuits are included in such codes: cable-to-cable, field-to-cable, antenna-to-antenna, and field-to-box. Figure 1 shows an example of an EM near-field cable-to-cable coupling model [11]. The induced noise voltages on the susceptible circuit ($V(Z_2)$ and $V(Z_L)$) have been coupled capacitively and inductively (through C_c and L_{12}) from the EMI source circuit (represented by source and load impedances Z_s and Z_1 respectively). Similarly, Figure 2 shows an analytical model for solving a far-field field-to-cable EMI problem [12]. In Figure 2 the solution for the induced current I_s can be obtained through the application of Stokes'theorem to integrate the equation $\nabla \times \mathbf{E} = -j\omega\mathbf{B}$ to obtain the expression $\int \mathbf{E} \cdot dl = -j\omega \int \mathbf{B} \cdot \hat{n}dS$. After a series of mathematical manipulations, involving transmission line theory, the expression for I_s in Figure 2 is obtained.

There are several computer codes written through the years which use analytical approximations, of the types discussed above, in the

solution of several types of EMC problems [8-9]. Students are briefly introduced to the use of these codes for the analysis of simple problems. Figure 3 shows a simple sketch of the types of problems that students can analyze using the codes in references 8 and 9.

ELECTROMAGNETIC COMPUTATIONAL APPROACH TO EMC MODELING

As the topology of the EMC problem becomes more complex, the need arises to consider alternate methods of solutions. The complexity in the modeling not only pertains to the different types of coupling modes but also to the complexity in modeling the diverse number of noise sources and susceptible circuits.

Highly evolved Electromagnetic (EM) codes have recently been used in the analysis of EMC problems [13-14]. The codes use highly mathematical techniques which are based on the rigorous physics of electromagnetic phenomena. The objective in introducing the students to these EM computational methods is to prepare them for solving more complex EMI problems. However, it is important that the students learn to recognize the limitations of these modeling tools, since EMC problems can have intricate topologies with many degrees of difficulties.

As a preliminary step, students are prepared in advanced areas of electromagnetic theory such as radiation, reflection, scattering,...etc. Upon this foundation the students are then introduced to several asymptotic and computational techniques which have been very useful in electromagnetics. The material is presented at the introductory level, avoiding an in-depth theoretical exposure of each of these subjects due to time constrains in the teaching. The format followed in the exposure of each of these computational techniques is: 1) introducing the students to a historical and theoretical background concerning the origin, derivation and applicability of a particular EM technique, and 2) teaching the students how such technique can be used to model and solve EMI problems. The students develop a fundamental understanding of the physics used in these codes; hence, becoming "intelligent" users of the codes, rather than merely using the codes for obtaining solutions. Table 2 describes the scope of the theoretical introduction presented to the students concerning several of the EM computational techniques. Table 3 provides a brief description of two widely known EM codes which can have applicability to EMC analysis. These codes are introduced to the students for their use.

TWO EXAMPLES IN THE USE OF "EM" COMPUTATIONAL METHODS FOR THE MODELING OF EMI PROBLEMS.

For the purpose of illustrating the type of problems taught in EMI modeling using EM computational methods, two examples are described which illustrate how useful some of these modeling techniques can be in solving a variety of interference-type problems. In both examples the Method of Moments is used. It must be emphasized that in EMC, sometimes the most difficult task is the proper modeling of the EMI problem; hence, students are taught only simple modeling cases during the course.

Example 1: Prediction of Radiated EMI from a PCB

One of the most effective contributions for EMC analysis in the area of proper design of multilayer Printed Circuit Boards (PCBs). This important subject started receiving considerable attention in the early 1980's when the FCC and European regulatory agencies started imposing radiated and conducted emission limits on all computing devices that use clock pulses above 10 KHz. For the first time there was a real incentive to minimize the amount of EM emissions from PCBs and associated parts which make up a computing device.

Several models have been developed through the years which have attempted to predict the amount of radiated EMI form PCBs. These models go from simple loop antenna models [15] to more complex transmission line models [16-17]. The students learn to appreciate quickly however, that EMI prediction from PCBs is a small portion of the total EMI picture that deserves serious attention when modeling the EMI from a computing device. For example, they're shown that the radiated noise from power and I/O cables due to common mode current is most often the major source of EMI from such devices [18]. Furthermore, the EMI analysis can become even more complex if scattering effects and coupling between elements from several PCBs in a device are considered.

With the objective of introducing the students to some fundamentals in EMI modeling, the task of predicting the levels of radiated electric fields from a portion of a PCB is pursued. The results obtained are compared with measured radiation. The measurements were made at an Open Field Test Site (OFTS). In this example the radiation associated with a clock signal generated on a multilayer PCB is analyzed using the method of moments. The system board of a personal computer was used. To keep the model simple and within the capability of the computer resources, only a small portion of the board was considered.

Board Description: The personal computer board selected for the evaluation was composed of five layers: Three signal planes, one

ground plane and one voltage plane. The spacing between each layer was 0.3556 mm and the total thickness of the board was 1.42 mm. A portion of the clock signal was selected. The remaining circuit was separated from the selected circuit by cutting the trace lines. The chips and components were left mounted on the PCB. The resulting circuit comprised four chips: two CMOS and two TTL, as shown in Figure 4. The crystal oscillator was connected to the clock chip, which generated the 12 MHz clock pulse with a 50 % duty cycle; rise time was 10 nS. The output of the clock chip was connected to the remaining four chips in shunt configuration . The board was supplied by a 5 V DC external source.

Measurements: The multilayer PCB and a horizontally polarized tuned dipole antenna were mounted at the fixed height of 1 m above a reflecting ground plane at an OFTS. The horizontal distance from the feed point of the antenna to the nearest point on the board was 3 m. The largest area of the board was oriented parallel to the reflecting surface with the components side up. The radiated signals were measured at all the odd harmonics from 36 MHz to 180 MHz.

Modeling Method: The reflecting ground plane was modeled as a wire mesh using 25 coordinated points interconnected with 40 equal-length straight round wire segments. For the multilayer board, the clock trace which connects the clock generator chip to the other chips utilized several signal planes. The traces were modeled by 19 different lengths of straight round wires. The board ground plane was modeled by using the method of images, i.e imaging the traces with respect to the ground plane. Since the rest of the circuit is nonactive and terminated by the impedance of the remaining chips and components, it was found that the induced currents on these nonactive traces are very small in comparison with the current flow on the active circuit. A 3-dimensional model representing the traces and their images is shown in Figure 5. A total of 74 wire segments were used in the model. The input capacitances of each chip ranging from 3 pF to 10 pF, were obtained from several data books. These component values are nominal in nature and no attempt was made to obtain the complex values of impedances .vs. frequencies which are needed for more accuracy in these models (data books on chips seldom provide this information). The reactances were calculated for the appropriate frequency and were connected to the clock trace at the chip location and the image points. Since the total thickness of the board was 1.42 mm, the board was considered very thin in terms of the wavelength of interest, and hence the dielectric material between layers was also very thin. The dielectric material was found to have a minimal effect on the total field. The squared trace cross-sectional dimensions were translated to the radius of equivalent round wires. The clock signal was modelled as a 12 MHz signal source with an amplitude of 5 V peak-to-peak situated midway between the top signal trace and its image trace as shown in Figure 5. The clock rise time and duty cycle were input to the program to calculate the amplitudes of the harmonics. These values are used to represent a radiating source amplitude at the corresponding frequency. For

example, at 36 MHz the radiated source used in the field calculation was 0.8444 V.

Results: The plots of the measured and calculated results, shown in Figure 6, cover the range 30-200 MHz. It can be seen from Figure 6 that high correlation of both data sets was obtained. The best correlation was obtained at 180 MHz, having a field intensity difference of 1 dB and a maximum difference of 8 dB at 36 MHz. The greater difference at the low frequency of 36 MHz is mainly due to near field measurement errors and the antenna factor. One would expect the measuring accuracy to increase the frequency as indicated for frequencies above 132 MHz.

Value to the students: When students learn the use of the method of moments technique for predicting the radiated emissions from a small portion of a PCB, the practical applications for the design and layout of more complex circuits becomes self-evident to them. Several questions related to the design of PCBs were raised by the students in this exercise: 1) what are the computational limitations as the analysis of a PCB becomes more complex ?, 2) how can the technique be applied for obtaining a PCB layout that would radiated the least ?, b) how can this methodology be implemented within a PCB layout CAD system for designing an optimun board (i.e in terms of least emissions) to comply with regulations.

Example 2. Calculation of a 3-m Site Attenuation.

The FCC and European regulatory agencies require that all equipment capable of producing radiated and conducted RF noise be tested in order to quantify the amount of noise they emit. The radiated measurements are usually made at an Open Field Test Site (OFTS). The OFTS is an open area which contains a metal ground plane, above which locations are designated for an Equipment under Test (EUT) and a measuring dipole antenna. The distance between the EUT and antenna is usually 3.0 meters, and the measurements are made for both horizontal and vertical polarization while the EUT is being exercised electronically. Because errors can occur in the measured values due to imperfections at the site (e.g the presence of obstructing features), it is important to "characterize" the site and measure its suitability for performing these emission measurements by calculating or measuring its site attenuation.

Site Attenuation Description: The Site Attenuation Measurements (SAM) were designed to "qualify" an OFTS for radiated emissions measurements. The qualification test is conducted by comparing theoretical and experimental values of a signal which is transmitted between two tuned-dipole antennas separated by 3.0 meters. One antenna is selected as the receiving antenna, the other one as the transmitter. The receiving antenna is scanned vertically between 1-4 meters while the transmitting antenna height is fixed at 2.0 m. Figure 7 shows an illustration of the measurement set-up

for SAM. A detailed procedure for calculation of SAM can be found in reference [19]. Published data however, reveals considerable discrepancy between experimental and theoretical values below 150 MHz. The reason for these discrepancies is that theoretical values were calculated: a) using far field theory, b) neglecting the coupling between the dipole antennas, c) neglecting the coupling of the dipole antennas and the ground plane, specially for vertical polarization.

Modeling Description: To evaluate SAM more effectively and to avoid the aforementioned discrepancies, the method of moments can be used. Accordingly, both dipole antennas over the ground plane are modeled as a number of segments. The number of segments is dependent on the physical sizes of the commercial tuned-dipoles used and the frequency range of interest (30 MHz-1000 MHz). In this example the maximum size of each dipole antenna used was about 2.5 meters. Theoretically, in order to provide good accuracy up to 1000 MHz using the method of moments code supplied to the students, each dipole antenna and its image should have been divided in 33 segments ($\lambda/4$), each segment with a length of about 7.5 cm each. However, because of the extensive amount of computations (computing time is proportional N^3, N being the number of segments) only 10 segments per dipole were used. Three different wire radi were used in the modeling (3.2 mm, 2.4 mm, 1.6 mm). Each wire radius corresponded to a frequency range used by the dipole (30-60 MHz, 60-340 MHz, and 340-1000 MHz). These frequency ranges correspond to the three different types of elements (rods) used in the dipoles. The galerking method with sinusoidal basis fuctions was used in the method of moments. Figure 8 shows the method of moments representation of the transmitting and receiving dipoles over the ground plane. In the figure V_t is the driving source voltage at the transmitting antenna. The method of moments calculates the mutual impedance between segments and self-impedances of each segment. The output current of each segment is determined by solving simultaneous equations which state that the boundary conditions on each segments are satisfied. The output voltage of the receiving antenna (V_r) is determined by the product of the output current at its center segment (calculated by the method of moments) and the input impedance of the receiver at the antenna end of the coaxial cable. The site attenuation (S_{atn}) is then calculated by $S_{atn} = V_t/V_r$.

Measurements and Calculations: Figure 9 shows the results of comparing the calculated values, using the method of moments, with measured values for vertical polarization. Figure 10 shows the results of comparing the calculated values, using the method of moments, with the FCC theoretical specifications (FCC does not consider vertical polarization for SAM). Notice that the discrepancies between measurements and calculations in Figures 9 and 10 do not exceed 3-4 dB. The allowed deviation between the FCC theoretical specification and measured results is 3 dB.

Value to the students: When students make use of the method of moments for calculating the site attenuation, they learn the usefulness of a computational technique which allow the easy modeling of a complex engineering problem based on the correct physics (e.g the need to account for mutual coupling between atennas and with the ground plane). If the modeling of the physics is correct, the measured results will corroborate with the calculated data.

CONCLUSION

In the fast developing field of electronics as IC chips become faster and the packaging of electronic devices decreases in size, electromagnetic compatibility problems are bound to increase. The teaching of EMC is important in a synthesis engineering education approach, since it teaches future engineers to consider good EMC practices in the design and manufacture of electronic devices. Though traditional EMC codes have emphasized limited analytical methods in their analysis of EMI problems, the use of electromagnetic computational methods has been shown useful in giving engineering students a broader spectrum for their analytical skills. These tools no only enhance the students' capabilities, but can serve as viable instruments for teaching some of the basic and important principles in EMC.

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RFI PROBLEMS IN TRANSMITTERS	BRIEF DESCRIPTION OF RFI PROBLEM	METHODS OF SUPPRESSION
Sideband Splatter[1]	Deviations from the required response law in the transmitter modulator causing spectrum broadening. AM/FM, SSB, DSB systems.	- Filtering
Internal Harmonic Generation[2]	Deviations from the linearity of a transmitter final amplifier	-Balanced circuits -Filtering -Wave trap
Intermodulation and Cross modulation[3]	Mixing of two or more signals in a non linear element. Resulting multiplicative mixture of both signals	-Filtering
Oscillator Noise	Similar to sideband splatter except at a lower level	-Filtering -Design of very good oscillators

In Table 1a the following applies:

(1) Output of nonlinear element plus narrowband filter centered at carrier ω_c. Input function is X_1.

$$\sum_{n=1}^{N} \sum_{k=1}^{n} a_n \binom{n}{k} X_1^{n-k} \frac{k!}{\left(\frac{k-1}{2}\right)! \left(\frac{k+1}{2}\right)!} Cos(\omega_c + \phi_c)$$

(2) output of nonlinear device is

$$y = a_o + a_1 x + a_2 x^2 + \ldots + a_k x^k$$

$$where \quad x = x_1(t) + Cos\, w_c\, t$$

(3) Let Signal 1

$$X_1(t) = m_1(t)\ Cos\,(\omega_1 t + \phi_1(t))$$

Let Signal 2

$$X_2(t) = m_2(t)\ Cos\,(\omega_2 t + \phi_2(t))$$

$X(t) = X_1(t) + X_2(t)$ go through a nonlinear device to obtain the result

$$y(t) = a_o + a_1 x + a_2 x^2 + a_3 x^3$$

For intermodulation:

$$y(t) = m_1^2(t)\ Cos[(2\omega_1 - \omega_2) + 2\phi_1(t) - \phi_2(t)] + higher\ order\ modes$$

For crossmodulation:

$$y(t) = m_1^2(t)\ m_2(t)[Cos\ \omega_2 t + \phi_2(t)]$$

Table 1a. RFI PROBLEMS IN TRANSMITTERS.

RFI PROBLEM IN RECEIVERS	BRIEF DESCRIPTION OF PROBLEM	METHOD OF SUPPRESSION
Broadband Noise	Noise from natural sources (thermal, shot, solar, atmospheric) or man-made (discharges, switching of electronic devices, antenna behavior)	-Limiting & blanketing before broadband noise is filtered in the IF amplifier
Co-Channel Interference	Signals from communication sources are assigned a frequency near the center frequency of receiver	-Good care in frequency assignment
IF Channel Interference	Penetration of unwanted signals centered at one of the IF channels of the receiver	-Selectivity of the input RF circuit and/or stray paths must be controlled
Spurious Response(4)	Nonlinearities in early stage gives rise to harmonics of incoming signals; nonlinearities in the mixer and frequency multiplication in local oscillator	-Filtering prior to mixer
Intermodulation & Crossmodulation (see Table 1a)	Intermodulation: when two or more unwanted signals are present at the input. crossmodulation:transfer of information from an undesired carrier onto the desired one	-Filtering
Desensitization	Reduction of receiver gain when a large unwanted signal enters the receiver	-Filtering prior to receiver

In Table 1b the following applies:

(4) Mixing operation:

if oscillator is $y_1 = A \cos \omega_1 t$

and signal is $y_2 = x_s(t) \cos(\omega_s t + \Phi_s)$

For non linearity

$$y = \sum_{n=0}^{N} b_n y^n$$

and the result of $y = y_1 + y_2$ is

$$\sum_{n=0}^{N} b_n \sum_{k=0}^{n} \binom{n}{k} x_s^k(t) \cos^k(\omega_s t + \Phi_s) A^{(n-k)} \cos^{(n-k)} \omega_1 t$$

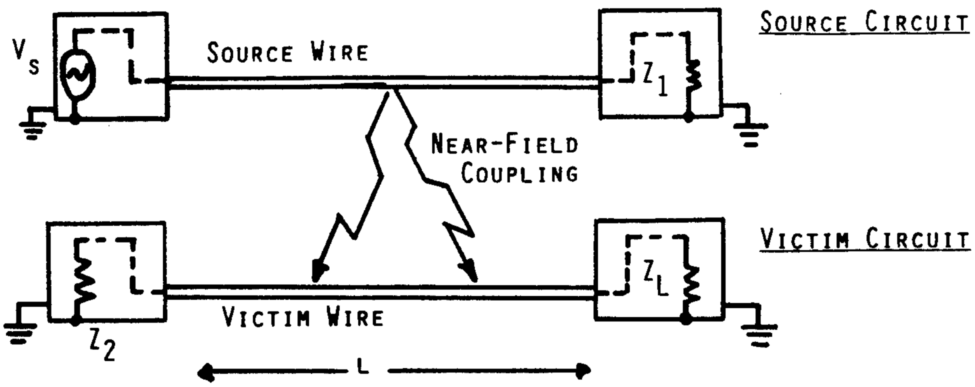
Table 1b. RFI PROBLEMS IN RECEIVERS.

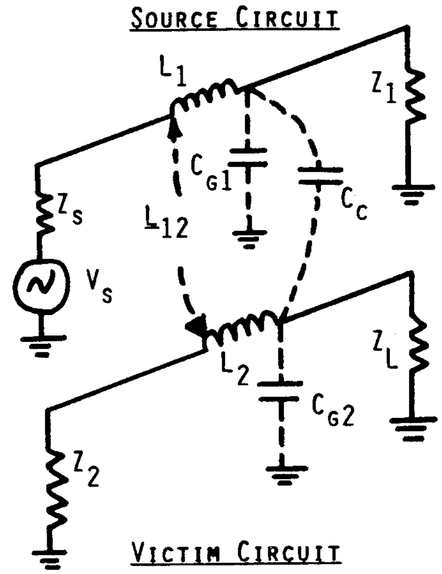
COMPUTATIONAL "EM" METHODS	BACKGROUND FROM MAXWELL EQUATIONS	APPLICABILITY	EXAMPLES OF USEFULNESS TO EMC
Finite Element Methods	Helmholtz equation. Dirichlet boundary condition. Ritz-Galerkin Method	Waveguide structure in microwave, millimeter wave and optical wavelength region	Electric and Magnetic fields in cavity-type structures
Method of Moments (MOM)	Electric and Magnetic field integral equations solved via expansion of basis functions	Antennas or any radiating structure that can be modeled correctly	Electric and Magnetic fields from physical antennas, and from cables, PCB traces..etc.
Spatial Network Theory	Differential form of Maxwell equations solved in time domain	Waveguide problems, wave penetration, reflection,dif fraction, radiation	EMP, coupling problems (field-to-cable) in near and far fields
Geometric Theory of Diffraction (GTD)	Expansion of geometrical optics. Results from asymptotic expansion of Maxwell's equations	Diffraction from conducting scatterers of almost any shape	Field-to-cable coupling where effects of the scattered incident filed is needed
Physical Optics & Physical Theory of Diffraction (PO/PTD)	similar to GTD, but induced surface current is separated: uniform and diffracted. Elementary edge waves are considered	Diffractions from large objects for which for which PO/PTD can be constructed	Field-to-cable coupling analyses between complex radiators and cables near large structures

Table 2. "EM" METHODS TAUGHT TO STUDENTS WITH APPLICABILITY TO EMC

NUMERICAL ELECTROMAGNETIC CODE (NEC)	GENERAL ELECTROMAGNETIC CODE FOR THE ANALYSIS OF COMPLEX SYSTEMS (GEMACS)
Capabilities: EM radiation, antenna performance, radar cross section,EMC. Emphasis is on accurate modeling of field emissions, field sources	Capabilities: EMC, EMP, ECM, ECCM, jamming susceptibility. EM radiation and scattering. Radar cross section. Emphasis is on modeling fields and field sources. Includes reflectivity, scattering conducting surfaces.
Outputs: Current distribution on wires and surfaces. Coupling between antennas. Near and far field strengths.	Outputs: Current distribution on wires, surfaces. Coupling between antennas. Scattering of conductive surfaces. Behavior of cavities
Physical Modeling: Electric Field Integral Equation (EFIE) via Method of Moments (MOM).	Physical Modeling: Electric Field Integral Equation (EFIE) via Method of Moments (MOM), Geometric Theory of Diffraction (GTD), Finite Element Method (FEM), Hybrid Models (MOM/GTD/FEM).

Table 3. DESCRIPTION OF TWO "EM" CODES TAUGHT TO THE STUDENTS.





L=LENGTH OF WIRES
L_1 = WIRE INDUCTANCE OF SOURCE CIRCUIT
Z_S = IMPEDANCE OF SOURCE CIRCUIT
C_{G1} = CAPACITANCE TO GROUND IN SOURCE CIRCUIT
V_S = VOLTAGE OF SOURCE CIRCUIT
Z_1 = LOAD IMPEDANCE OF SOURCE CIRCUIT
C_C = COUPLING CAPACITANCE
Z_2 = SOUCE IMPEDANCE OF VICTIM CIRCUIT
Z_L = LOAD IMPEDANCE OF VICTIM CIRCUIT
C_{G2} = CAPACITANCE TO GROUND IN VICTIM CIRCUIT
L_{12} = MUTUAL INDUCTANCE

$$V(Z_L) = \frac{j2\pi f l \dfrac{Sin(\beta L)}{\beta L} Z_L[C_c Z_1 Z_2 - L_{12}] V_s}{[---]}$$

$$V(Z_2) = j2\pi f l \frac{Sin(\beta L)}{\beta L\,[---]} Z_2\Big[[Cos(\beta L)\,[Z_L Z_1 C_c + L_{12}]] + j2\pi f l \frac{Sin(\beta L)}{\beta L}[Z_L C_c L_1 + Z_1 L_{12}(C_{g1}$$

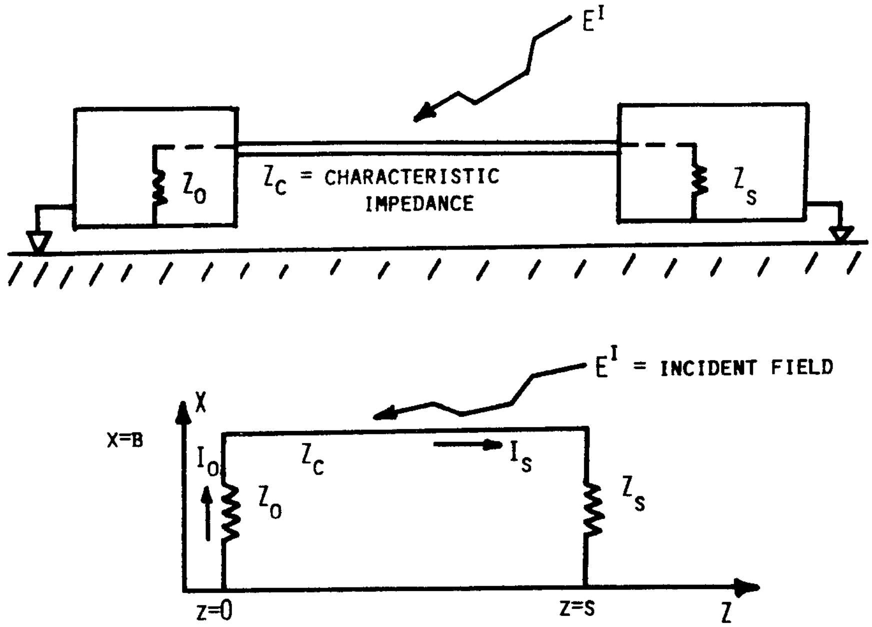
where

$$[---] = (Z_s + Z_1)(Z_2 + Z_L)\,Cos^2(\beta L) -$$

$$j4\pi^2 f^2 l^2 \frac{Sin^2(\beta L)}{(\beta L)^2} [[Z_1 Z_s (C_{g1} + C_c) + L_1][Z_2 Z_L (C_{g2} + C_c) + L_2] - [L_{12} - C_c Z_s Z_1][L_{12} - C_c C_1 Z_2]] +$$

$$j2\pi f \frac{Sin(\beta L)}{\beta L} Cos(\beta L)\,[\,(Z_2 + Z_L)\,[Z_1 Z_s (C_{g1} + C_c) + L_1] + (Z_s + Z_1)\,[Z_2 Z_L (C_{g2} + C_c) + L_2]]$$

Figure 1. CAPACITIVE & INDUCTIVE NEAR FIELD COUPLING



$$I_o = \frac{1}{[---]} \int_0^s P(z)\left[Z_c \operatorname{Cosh}\gamma(z-s) - Z_s \operatorname{Sinh}\gamma(z-s)\right]dz -$$

$$\frac{Z_c}{[---]}\int_0^b E_x^i(x,s)\,dx + \frac{Z_c \operatorname{Cosh}\gamma s + Z_s \operatorname{Sinh}\gamma s}{[---]}\int_0^b E_x^i(x,0)\,dx$$

$$I_s = \frac{1}{[---]} \int_0^s P(z)\left[Z_c \operatorname{Cosh}\gamma(z) - Z_o \operatorname{Sinh}\gamma(z)\right]dz -$$

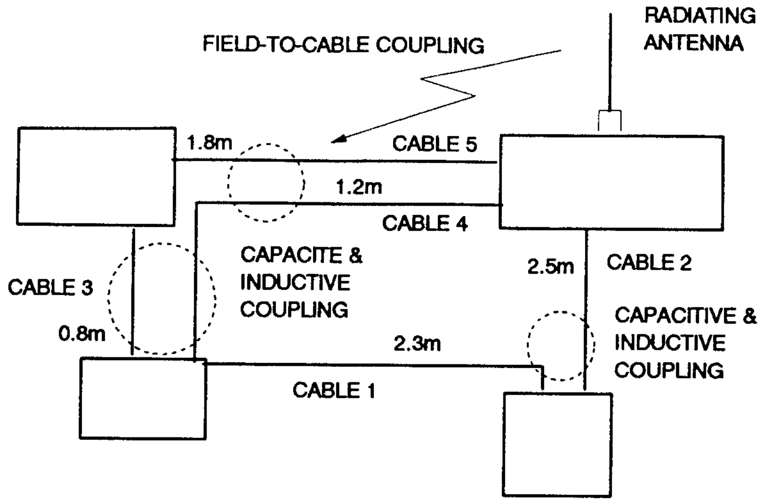
$$\frac{Z_c}{[---]}\int_0^b E_x^i(x,0)\,dx + \frac{Z_c \operatorname{Cosh}\gamma s + Z_o \operatorname{Sinh}\gamma s}{[---]}\int_0^b E_x^i(x,s)\,dx$$

<u>where</u>

$$P(z) = \left[E_z^i(b,z) - E_z^i(0,z)\right]$$

$$[---] = [Z_c Z_o + Z_s Z_c]\operatorname{Cosh}\gamma s + \left[Z_c^2 + Z_s Z_o\right]\operatorname{Sinh}\gamma s$$

<u>Figure 2. FIELD TO WIRE COUPLING</u>



Example:

cables 1&2 are shielded, 3,4 & 5 unshielded
cables 1&2 are AWG 20, cables 3, 4 & 5 AWG 22
shield thickness of cables: 1.2 mm
dielectric constant of insulators for all cables: 3.2
Source & Load impedances are given for each circuit
Height above ground plane: 8.0 cm
capacitances to ground:cables 1&2=15pF;cables 3,4&5:20pF
coupling capacitances between cables are given

FIGURE 3. TYPICAL EMC PROBLEM ANALYZED USING ANALYTICAL METHODS

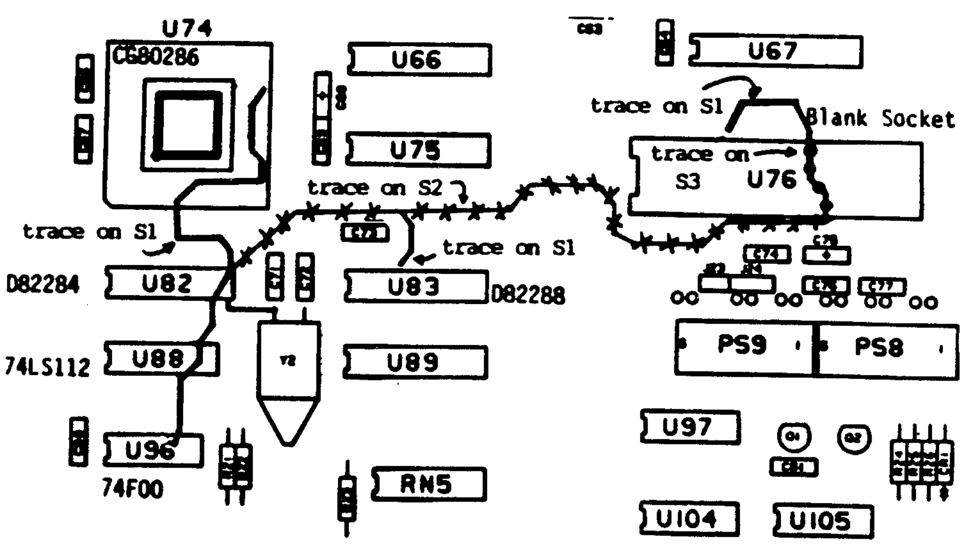


FIGURE 4. PORTION OF A CLOCK CIRCUIT ON THE MULTILAYER BOARD.

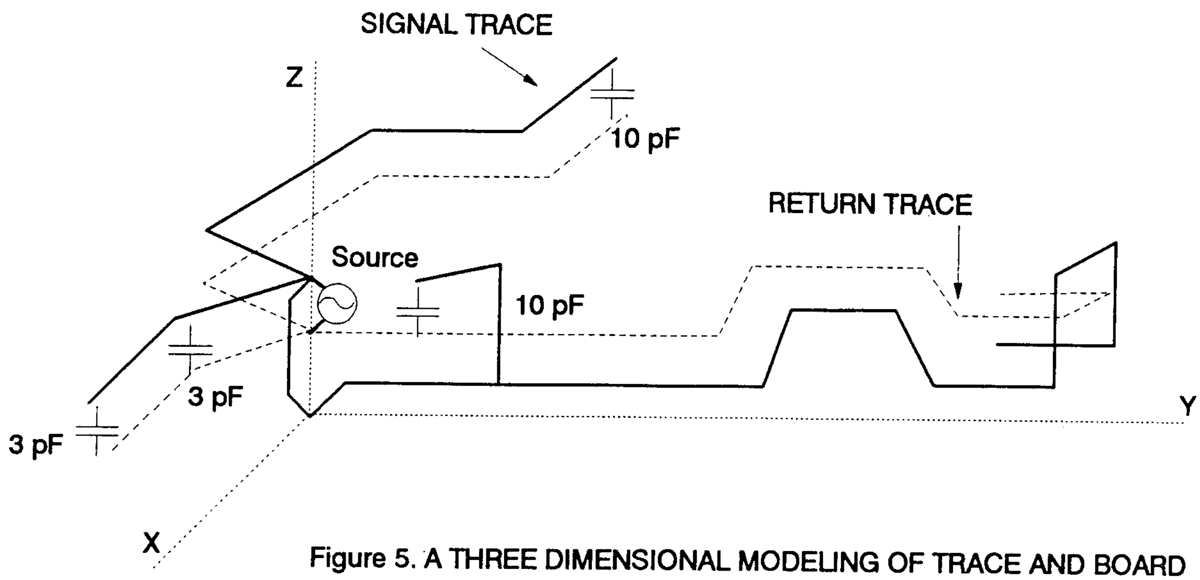


Figure 5. A THREE DIMENSIONAL MODELING OF TRACE AND BOARD

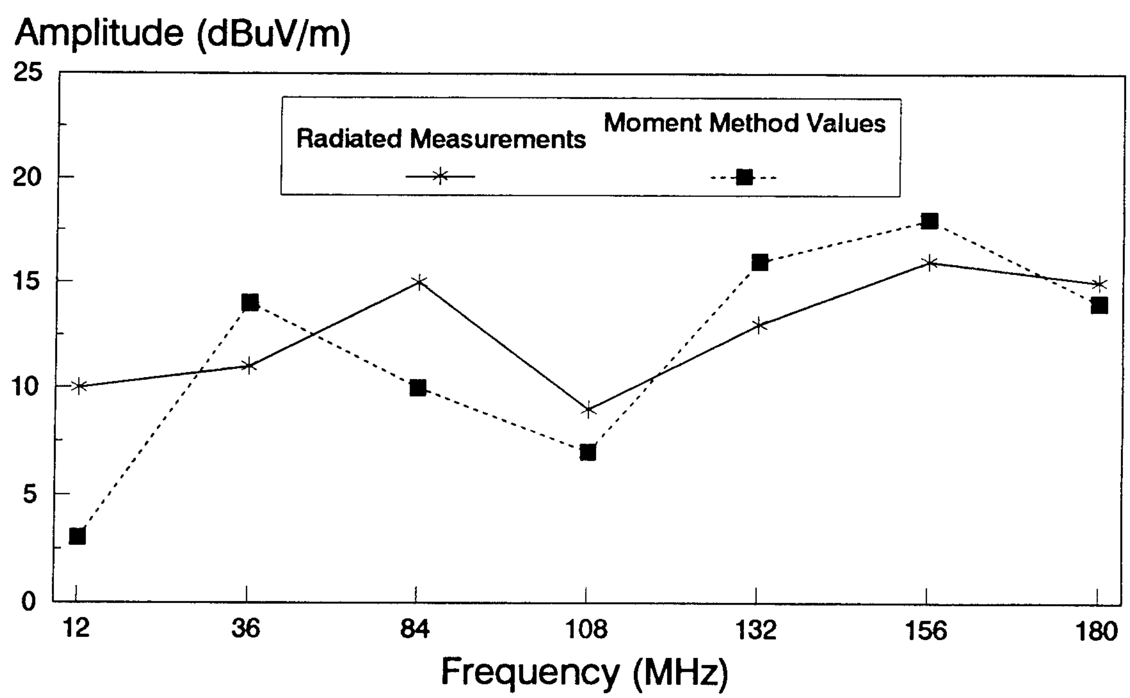


FIGURE 6. AN ELECTRIC FIELD COMPARISON BETWEEN MEASURED DATA AND MOMENT METHOD DATA.

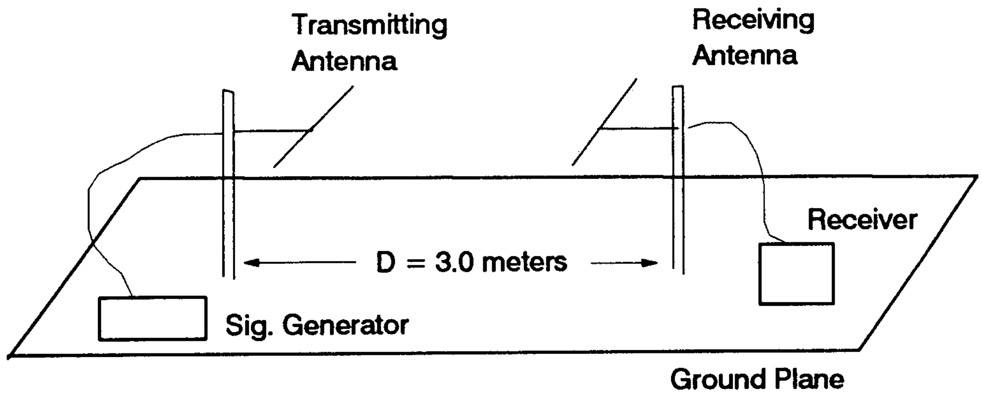


FIGURE 7. MEASUREMENT SET-UP FOR OBTAINING SITE ATTENUATION

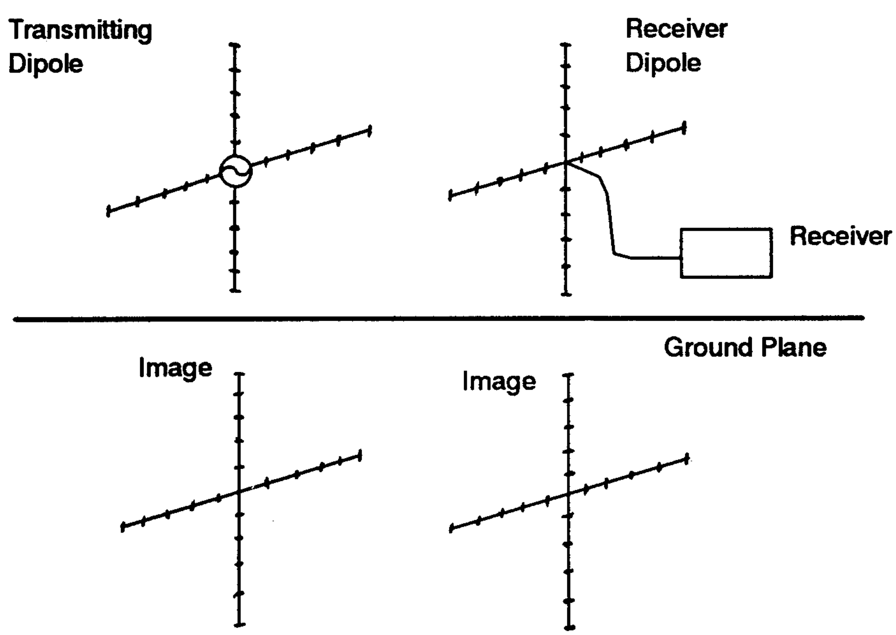


FIGURE 8. MOMENT METHOD MODELING FOR VERTICAL AND HORIZONTAL POLARIZATIONS FOR SITE ATTENUATION CALCULATIONS

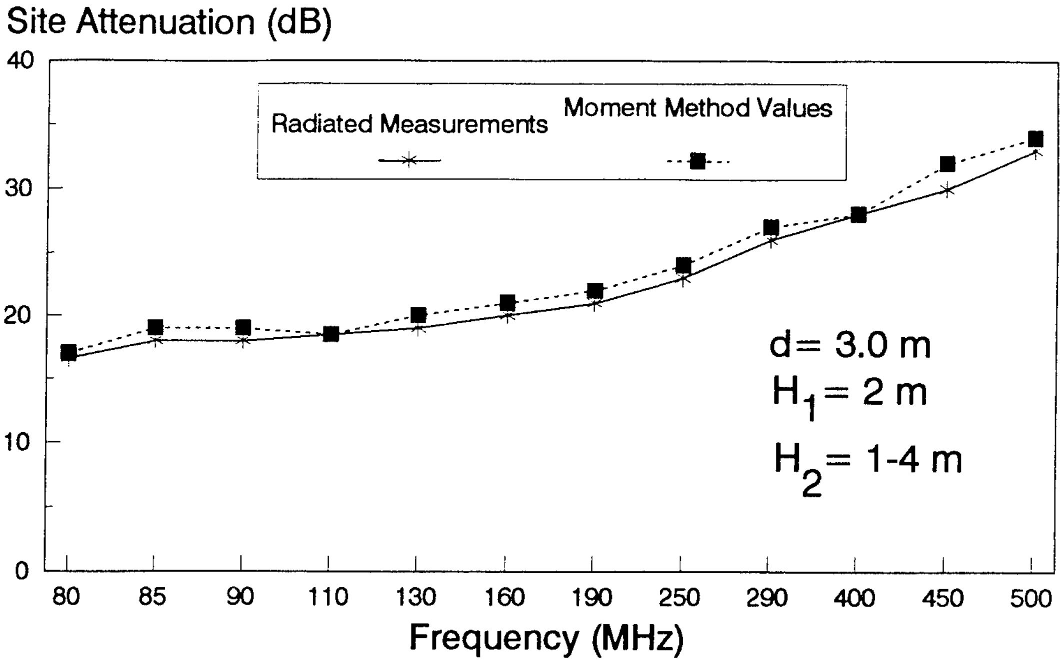


FIGURE 9. COMPARING MEASURED AND CALCULATED RESULTS FOR VERTICAL POLARIZATION USING THE METHOD OF MOMENTS

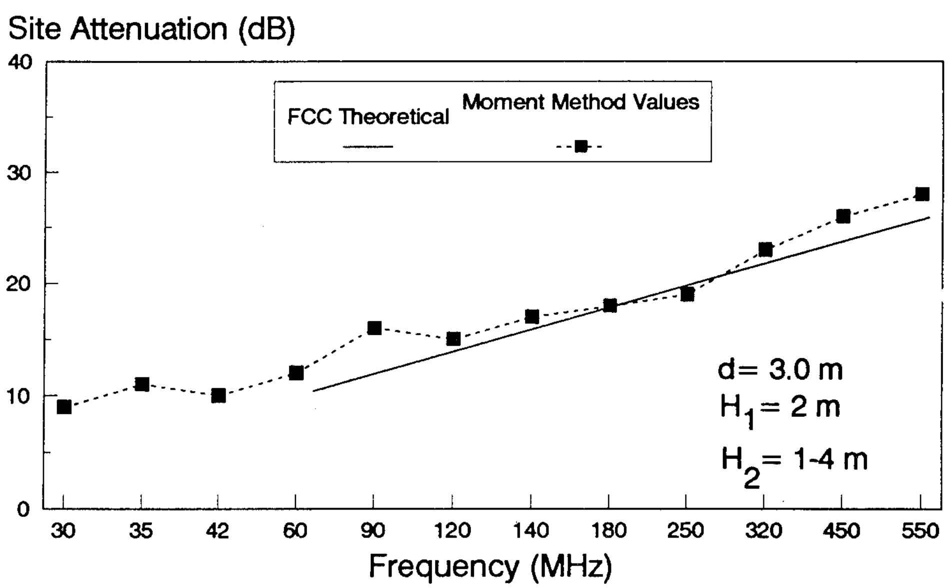


FIGURE 10. COMPARING THE FCC THEORETICAL SITE ATTENUATION FOR HORIZONTAL POLARIZATION WITH METHOD OF MOMENTS

Simple Techniques For The Desk-Top Production Of Computer Movies Which Illustrate Fundamental Concepts In Electromagnetics

by

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Abstract

Using Macintosh® computers and a selection of readily available commercial software, computer animations that effectively illustrate fundamental concepts in electromagnetics can be quickly and easily produced. The methodology, typical movie preparation, and the software and hardware requirements are discussed.

Introduction

Electromagnetic phenomena tend to be four-dimensional, represented by vectors that depend on the spatial coordinates and time. To facilitate their mathematical description, they are generally expressed as complex phasor vector fields, masking their time-varying nature. This complexity can make it difficult for the beginning student to visualize correctly the wide range of fundamental abstractions and principles which come into play in time-varying electromagnetism.

It is generally agreed that the use of computer movies can greatly enhance classroom presentation of these phenomena, and programs such as *TLS: Transmission Line Simulator*, developed by Charles H. Roth [1], have been well received by the electrical engineering undergraduate students at our university. However, movies to address the full range of fundamental concepts that must be dealt with in typical electromagnetics courses are not widely available to individual instructors.

Previously reported efforts to generate such movies have often required rather specialized hardware and a considerable investment in time by the instructor for the preparation of each movie, and have provided virtually no practical guidance to aid an instructor in generating such movies to augment his or her own lecture presentations [2,3,4]. Lately, very sophisticated mathematical analysis software, which incorporates animation features, notably *Mathematica* [5], has become popular. However, because of their complexity, such programs are very difficult to master quickly, and are often limited in their presentation capabilities.

This paper presents a very simple — yet flexible — approach to the preparation of computer movies. Using Apple Macintosh® computers equipped with typical office productivity and desk-top presentation software, an individual instructor can personally author a sophisticated movie and tailor it to his or her needs. A typical movie can be planned and prepared at the instructor's desk in a matter of a few hours at most, and classroom presentation will be seen to be as simple as using an overhead projector. The basic methodology for preparation and presentation of a movie, and the software and hardware requirements will be discussed.

Preparation of a movie

The phenomena that are to be displayed in a movie are time-varying, though not necessarily time-harmonic. The period of time over which the phenomena are to be

observed is divided into equally spaced time intervals. The objective is to choose a sufficient number of intervals so that the phenomena change only marginally from frame to frame, but not so many as to incur unnecessary labor in the preparation of additional frames. For time-harmonic phenomena, 24 frames per cycle are generally satisfactory, while the number of frames can vary widely for non-harmonic cases. One image of a phenomenon is produced for the beginning of each time interval. These images, or frames, are then recorded and played back sequentially as a movie.

For time-harmonic phenomena it is convenient to loop the sequence into an endless display. The speed at which the movie runs may be varied for optimal effect, or the movie can be advanced a single frame at a time. Such film strips, with explanations supplied by the instructor during presentations, are generally adequate. However, several filmstrips can easily be assembled to form a completely self-explanatory composite movie with titles and equations. All the steps that are necessary to produce a movie are implemented in "off the shelf" software packages so that no intricate programming is required. Even novice computer users who have a basic familiarity with the Macintosh environment can quickly become proficient at creating their own movies.

In all cases an equation or several equations have to be established that describe the curve or surface which is characteristic of the phenomena that are to be graphically displayed, such as a distribution of field amplitude or the location of lines of force. These equations contain one or more spatial variables and time. The equations must first be evaluated at the beginning of each time interval for the coordinate locations that define the space in which the phenomenon is to be viewed. There are a number of software programs available for the Macintosh computer that can display curves and surfaces with as little effort as typing in the equation or equations. Such programs as *Matlab* [6], *Systat* [7], *Theorist* [8], and *Mathview Professional* [9]

present the data in a variety of graphical formats. The images so created can be stored in the *Scrapbook*, a standard feature of the Macintosh operating system.

Alternately, spread sheet programs, such as *Microsoft Excel* [10], or user programs written in Fortran or other languages, can be used to evaluate the equations and to write tables of coordinates as text files. Raw numerical data produced in this way can be easily imported into a suitable graphing program, such as *Excel's* Chart window, *Cricket Graph* [11], or indeed into one of the programs previously mentioned, such as *Matlab* or *Systat*, where the images can be rendered and stored as before.

The approach selected is largely a matter of choosing the desired level of sophistication of the graphical output. Programs such as *Cricket Graph* provide elaborate 2-D graphics with control of axes, labelling, line width, font and so on, but cannot be used in the numerical evaluation of the equations. On the other hand, programs such as *Matlab* provide basic 2-D and 3-D images, but with little editing control of the images.

The final assembly of images into film strips can be achieved with any one of a number of animation programs. The authors have found *Video Works II* [12] entirely satisfactory. It is extremely easy to use and incorporates a basic drawing capability that permits the editing and enhancement of graphical images, as well as the addition of text. The makers of *Video Works II* have now replaced this program with a more powerful program called *Director 3.1* [13]. Assembly of images is quite similar in these two programs (*Video Works II* is upward compatible). Instructors interested in producing filmstrips may also wish to investigate the capabilities of *Mathematica*, *Maple* [14], *Apple Quick Time* [15], and *Delta Graph* [16], which have a variety of capabilities for producing graphic images and/or filmstrips. However, the authors have found that the greatest versatility and control for producing film strips, and in particular for linking them together and producing complete movies, resides in *Video Works II* and *Director 3.1*.

The general approach outlined above will now be illustrated with two examples. Variations on the particular steps involved will be apparent to those familiar with the Macintosh environment.

Sample Movie #1

The authors have developed a number of companion filmstrips to support classroom discussion of the reflection and transmission of plane waves at the interface between two dielectric half-spaces. Some of these strips are organized to depict simultaneously the instantaneous amplitudes of the individual component signals, i.e. the incident, reflected and transmitted signals in the two regions. Others illustrate the variation of the total instantaneous fields within the static envelope curve that defines the phasor field magnitude, and which is superimposed on each frame. In each case the simple steps outlined below, which pertain to the creation of the instantaneous field amplitudes, were followed in creating and assembling the 24 individual frames comprising the filmstrip. A typical frame from a filmstrip is shown in Figure 1.

1. *Formulate*

The electric fields are expressed in the two regions by the standard expressions

$$e_1 = E_o e^{-\alpha_1 z} \cos(\omega t - \beta_1 z) + E_o |\Gamma| e^{+\alpha_1 z} \cos(\omega t + \beta_1 z + \phi)$$

$$e_2 = E_o |\mathrm{T}| e^{-\alpha_2 z} \cos(\omega t - \beta_2 z + \theta)$$

where $\Gamma = |\Gamma| \angle \phi$ is the reflection coefficient

and $\mathrm{T} = |\mathrm{T}| \angle \theta$ is the transmission coefficient.

The objective is to present this *e*-field information in a conventional 2-D graphical format with the horizontal axis coinciding with z, the direction of propagation, and with the vertical axis representing the instantaneous field amplitude.

2. *Calculate*

A convenient way to evaluate these expressions is with a spreadsheet program. The authors used *Excel* by *Mircosoft*, which is one of the most popular and versatile such programs for the *Macintosh* computer. *Excel* provides a matrix of cells defined by rows and columns. Into each cell can be placed a number, or an equation that will be automatically evaluated in terms of numbers stored in other cells. There is no unique way to organize these cells to evaluate the above equations, however, the following suggestion works well for the present example. The description is brief and is not intended as a lesson on the use of a spreadsheet. Rather, it is included to indicate the remarkable ease with which the necessary equations can be calculated the several thousand times necessary to provide values for the field at each of 100 to 200 axial locations for 24 separate instances of time. The mechanics of the construction of the spreadsheet will be obvious to anyone familiar with this type of program and are, in any case, well described in the *Excel* documentation.

As shown in Figure 2, cell $R1C1$ (row 1 - column 1) is left empty and in $R1C2$ to $R1C25$ are stored the 24 individual times, $t1$ to $t24$, at which the signals are to be determined. This storage is accomplished by entering only the first time and then inserting a formula that will cumulatively and automatically increment each adjacent cell by a time interval equal to the period, T, divided by 24. For reasons that will become obvious, this procedure is then repeated for $R1C26$ through to $R1C49$. Then, in column 1 are stored the individual, equally spaced, axial locations at which the fields will be evaluated. For example, if there are 101 axial locations, cells $R2C1$ to $R52C1$ would be filled with $z1$ to $z51$, and cells $R53C1$ to $R103C1$ would be filled with $z51$ to

$z101$ ($z51$ designates the location of the interface at which the reflection takes place). Again, this is accomplished automatically by storing a first axial location and using an appropriate incrementing formula. Next, the correct incident wave formula is inserted into each of the matrix of cells defined, for this example, by the space $R2C2$ to $R52C25$, in such a way that the field value at an axial location z_i and time t_j will be automatically calculated and stored in cell $R_{i+1}C_{j+1}$. Again, it is not necessary to manually insert thousands of individual equations. The program automatically inserts an appropriately modified version of one representative equation, stored in an arbitrary location, for instance the upper left cell R2C2, as shown in Figure 2, into a predefined block of cells by means of "relative addressing." This procedure is repeated for the transmitted wave over the space defined by $R53C2$ to $R103C25$, and for the reflected wave over the space defined by $R2C26$ to $R52C49$. The complete construction of this spread sheet, which will contain the data for the entire filmstrip, can be accomplished in well under an hour. *Excel* permits storage of the results in text format, allowing other programs, such as *Cricket Graph*, to read the data directly.

3. *Graph*

The next step is to prepare the 24 individual graphical images that will comprise the filmstrip. The popular and easy to use application *Cricket Graph* was used for this purpose. *Cricket Graph* can directly open and read the data stored in step 2, and organize it into a row and column format identical to that of *Excel.* The first row of data containing the time intervals is then deleted. The remaining columns of data can now be manipulated and plotted in an almost limitless number of ways. In the present example, a 2D-plot is desired with Column 1 (the axial locations) as the horizontal axis, and some combination of the other columns (the field values at various times) representing the vertical axis. For example, selecting a plot of column 1 versus columns 2 and 26 produces a graph showing the individual values of the incident,

reflected and transmitted fields at time $t1$ over the range of z values defined in step 2 . On the other hand, the instantaneous total fields in both dielectric half-spaces can be displayed at time $t1$ by adding columns 2 and 26, storing the result in say column 50, and by then plotting column 1 versus column 50. Such manipulations of the data are easily accomplished in *Cricket Graph*. Also, once the desired graphical image has been generated the axes may be labelled with any desired font, the image may be resized, and additional text, legends, arrows, and so on, may be added. Using this method, all of the 24 individual frames are created. They are then stored by copying them to the *Clipboard* and then into the *Scrapbook* (standard features of the *Macintosh* operating system.)

4. *Assemble*

The 24 frames are now assembled to form a filmstrip that will run as a continuous loop depicting the instantaneous field variations in the vicinity of the dielectric interface by using the program *Video Works II* (or its successor *Director 3.1*). This software program is well documented and supports a wide variety of editing options. (For example, the shading of the dielectric region in Figure 1 was added in *Video Works II*.) The process is as simple as copying the stored images to a "cast window", shown in Figure 1. From the cast window, cast members are moved onto the "stage" in the order in which they are to be shown, simultaneously creating a movie "score." Assembly of a movie, once the graphical images have been created and stored (steps 2 and 3), rarely takes more than a few minutes.

Sample Movie #2

The preparation of this movie demonstrates the use of the software application *Matlab* to evaluate the equations that define the phenomenon to be studied and to

simultaneously graph the results. The filmstrip selected for this example is one of a number of strips that have been produced by the authors to aid the student in picturing dipole radiation. It depicts the variation with time of the distribution of the instantaneous amplitude of the total radiation magnetic field in the horizontal plane of two vertical dipoles separated horizontally by 0.75 wavelengths (λ), and excited 90° out of phase. A 3-D surface plot is generated by plotting the magnetic field amplitude on the vertical axis over a square grid $6\lambda \times 6\lambda$ centered at the origin. Figure 3 illustrates a typical frame from the completed film strip, which was created in the following manner.

1. *Formulate*

In this case the total radiation magnetic field in the horizontal plane can be written simply as

$$h = \frac{\cos(\omega t - \beta R_1 - 90°)}{R_1} + \frac{\cos(\omega t - \beta R_2)}{R_2}$$

where $R_1 = \sqrt{(x-d)^2 + y^2}$

$$R_2 = \sqrt{(x+d)^2 + y^2}$$

when the two dipoles are located on opposite sides of the origin at $(\pm d, 0, 0)$.

2. *Calculate and Graph*

Matlab is a versatile matrix oriented mathematical calculation and graphing program with its own high level, formula-like command language. Its use is easy to learn and well documented. In order to evaluate and graph the above field expression, a simple program (called a script) is written. It is included here to illustrate the simplicity of the procedure. (It has been assumed that the wavelength is one meter.)

`wt = 0;` (this value is changed for each frame)

```
[x,y] = meshdom (-3.0:0.1:3.0,-3.0:0.1:3.0);
h=cos(wt-pi./2-2.*pi.*sqrt((x-d).^2+y.^2))./sqrt((x-d).^2+y.^2)+...
cos(wt-2.*pi.*sqrt((x+d).^2+y.^2))./sqrt((x+d).^2+y.^2);
mesh (h)
```

This short program automatically evaluates `h` over a grid of 3721 points and produces a 3-D surface plot similar to the one shown in Figure 3. The program is executed once for each time interval with an appropriate value for `wt`, and the resulting graphical image is copied to the *Clipboard* and stored in the *Scrapbook.* Several additional lines of coding are required to limit the vertical scale of the plot to the same maximum and minimum values for each frame.

3. *Assemble*

The graphical images are assembled into a filmstrip using *Video Works II* as previously described.

These two simple examples illustrate that the actual preparation of a movie is quite straightforward. The major task is the initial creative effort needed to decide what one wishes to demonstrate. The authors have produced, and incorporated into their classroom presentations, many such filmstrips designed to illustrate specific conceptual points on such topics as

- wave reflection and transmission (normal and oblique incidence)
- total internal reflection and Brewster angle
- quarter wave window
- wave polarizations
- phase and group velocities
- distribution and propagation of fields in waveguides
- eddy currents in metal strips
- skin depth
- current and charge distributions on wire antennas
- electric lines of force in dipole radiation

- phased arrays

Projection

While small classes may view the movie on the computer monitor itself, some means of projecting the image will generally be required. One could for instance, prior to class time, photograph the computer screen as the movie runs with a conventional movie camera for later projection. One could also record the movie on videotape. There are several commercially available systems for large screen projection of such video images. Such "canned" presentations, however lose some effectiveness because the instructor can no longer easily replay, stop-start, step forward one frame at a time, and so on, as is often desirable in stressing specific points related to the movie.

A much simpler and more flexible approach (and used exclusively by the authors) is to use the *Kodak Datashow HR/M Projection Pad* (now handled by *Sayett Technology*, Rochester, N.Y.). This device is a transparent liquid crystal screen about the size of a large book. It operates on the video output of the *Macintosh*, taken through a video adapter that is included with the projection pad and which must be installed in the computer. The screen image is projected by simply placing the device onto an ordinary overhead projector as one would with any other overhead transparency. Figure 4 illustrates the simplicity of the basic setup. This projection pad, and other similar ones, such as the *3M 4100 Projection Panel*, do, however, have a rather long refresh time. This may limit the number of frames/second that can be clearly displayed. An alternative is to use a more costly projection pad, such as the *3M 5800 Active Matrix LCD Panel*, which has a very much smaller refresh time.

System Requirements

Most of the software mentioned above for the preparation of a filmstrip can be used on any currently available Macintosh computer. However, the professional versions of *Systat* and *Matlab* require a math coprocessor. Moreover, systems without coprocessors are limited to rather low frame speeds when running *Video Works II.* A hard disk is necessary. The authors have been using a Mac SE/30 system with 8 MB RAM and an internal 80 MB hard disc.

Conclusions

The classroom use of instructor-generated movies has been found to be very effective as an aid for teaching fundamental concepts in electromagnetics. These movies are easy to prepare, can be easily structured to reflect an instructors preferred style of teaching, and can be integrated into a lecture as easily as any other overhead illustration. Indeed, the projected film strip is an overhead "come alive" that provides a learning experience against which no amount of conventional blackboard illustration can compete. The movies produced by the authors have been well received in the classroom. They have helped students to clarify important concepts, have stimulated student thought, and have heightened student interest in the study of electromagnetics.

Use of computer movies is now an integral part of two introductory courses on electromagnetics and a course on antennas taught by the authors at the University of Alberta. Further movies on additional topics in electromagnetics are in preparation. As well as using movies in the classroom, a bank of computer movies is being created to which students will have independent access to review important fundamental concepts that were introduced as lecture material.

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16. *Delta Graph:* DeltaPoint, Inc., 2 Harris Court, Suite B-1, Monterey, CA 93940.

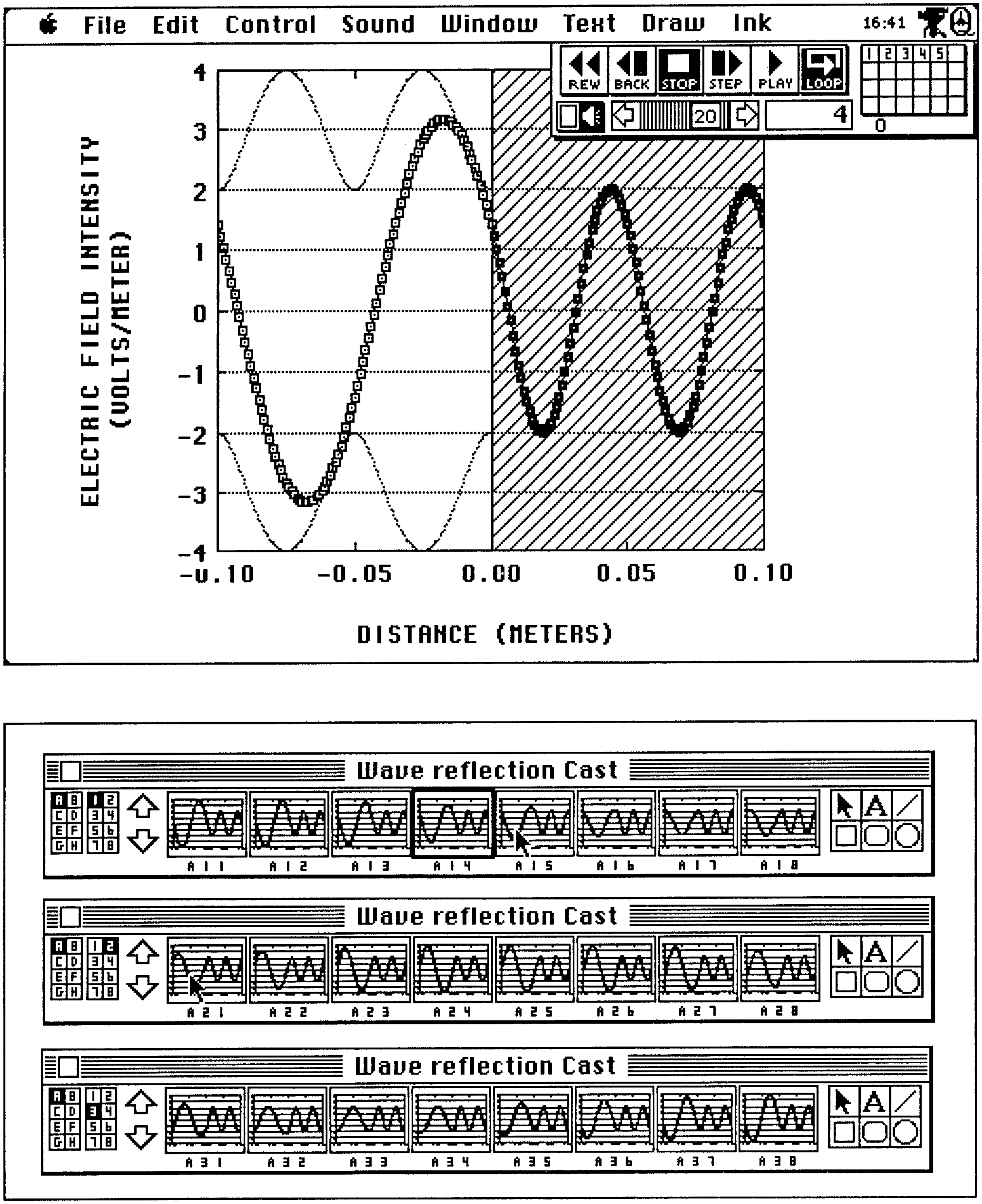

Fig. 1. Instantaneous electric field amplitude of a wave in free space, normally incident on a dielectric half-space of relative dielectric constant 4. The standing wave pattern is designated by lightly dotted lines. Also shown is the cast of 24 frames, which, when assembled, form a film strip.

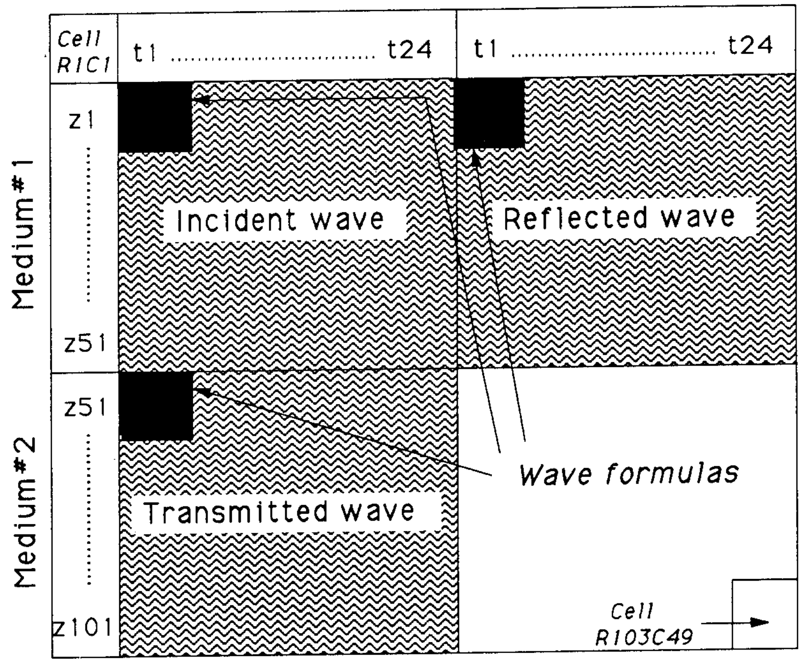

Fig. 2. The construction of the *Excel* spreadsheet, showing the cells allocated for the successive frame times and the axial positions for the incident, reflected, and transmitted waves.

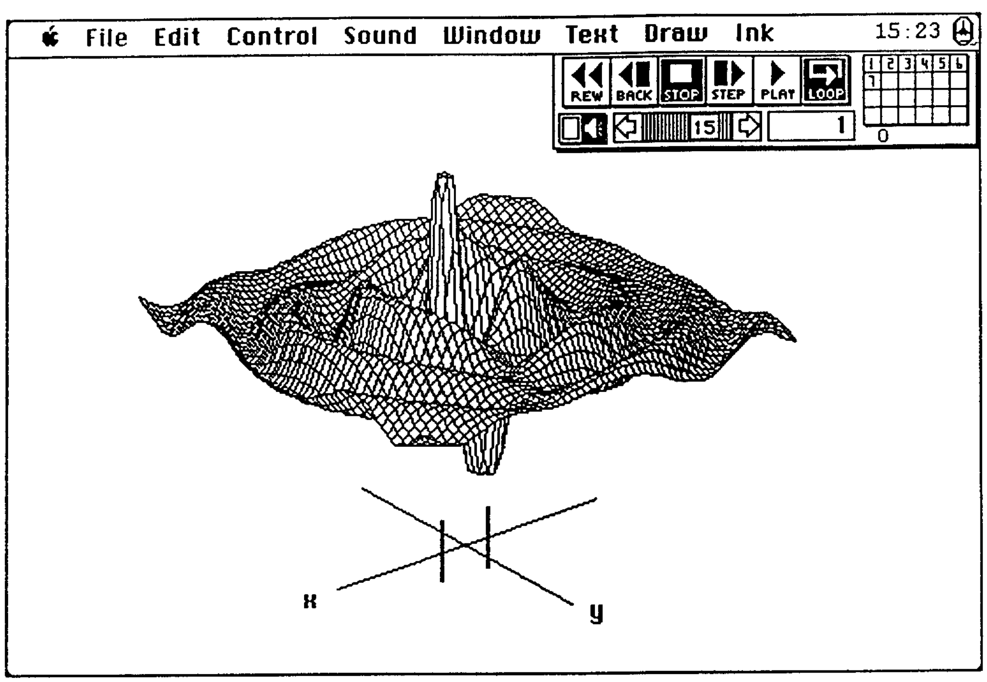

Fig. 3. Instantaneous amplitude of the radiation magnetic field in the principal H-plane of two vertical dipoles, for the case where the dipoles are separated by 3/4 wavelengths and excited in time quadrature.

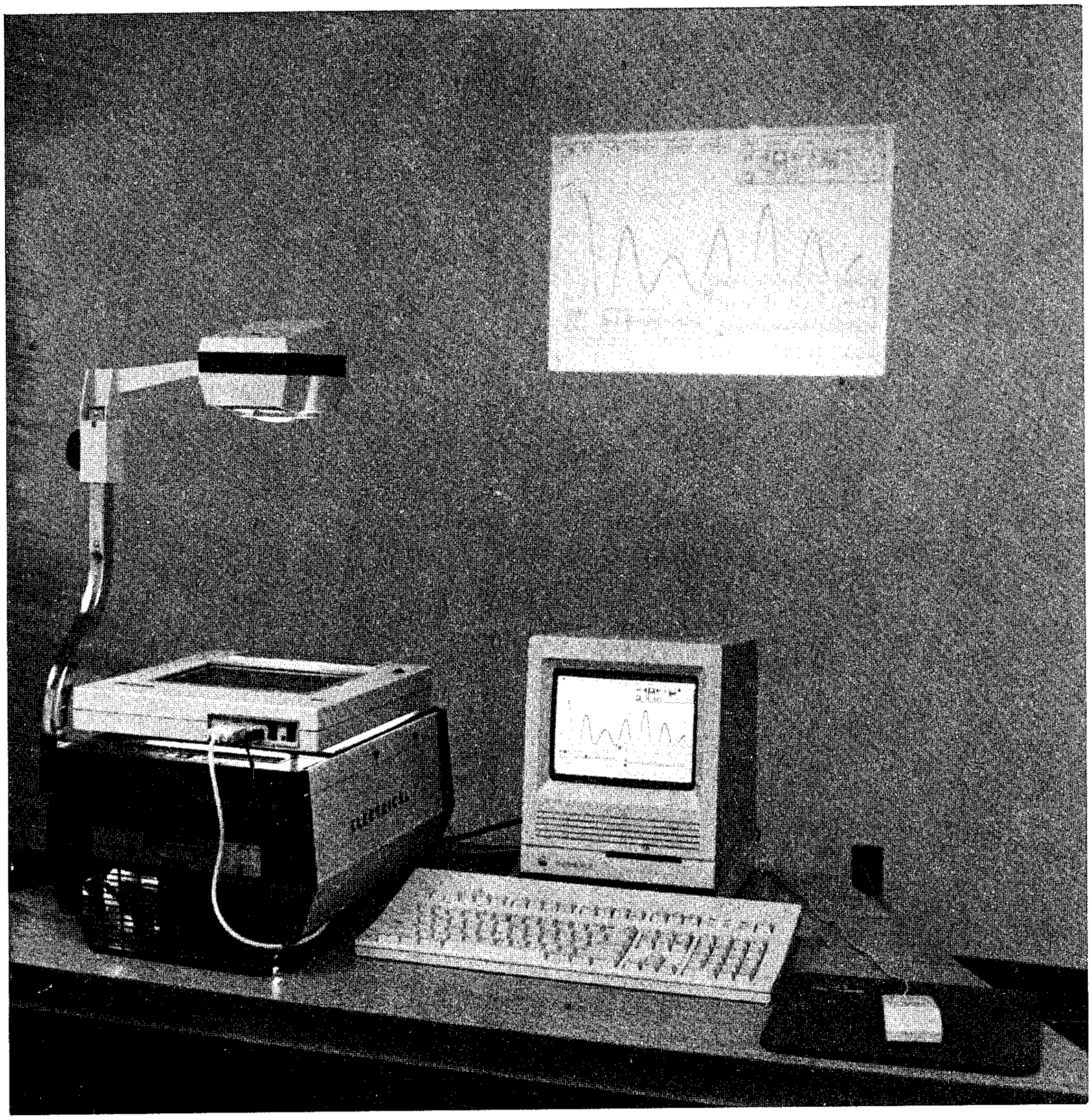

Fig. 4. The simple hardware required for movie projection consists of a *Macintosh* computer, an ordinary overhead projector, and the *Kodak Datashow HR/M Projection Pad* or similar device.

A GLOBAL APPROACH TO TEACHING NEAR-FIELD ANTENNA MEASUREMENTS

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ABSTRACT

A complete set of experiments on near-field antenna measurements is presented. This labwork serves two purposes: first, it introduces students to the difficulties associated with such a measurement technique, and second, they gain the confidence to work in high tech, elaborate environments. The technical goal in this labwork is to obtain the radiation pattern of an antenna through measurements of the near-field using a complete experimental set-up driven by a Macintosh computer, and performing a near-to-far field transformation using a combination of Helmholtz equation and the Fourier Transform. Actually, the knowledge students acquire in this labwork is built up in stages which are both independent and experiments in their own right: they are described in detail in the paper, along with the knowledge built up at each stage by students as they advance into the labwork, and the objectives achieved.

I. INTRODUCTION

Near-field antenna measurements is an advanced, highly sophisticated labwork, designed to introduce Supélec's[4] graduating students to a very specialized and narrow practice, with applications in such high tech areas as radars, space, antenna diagnostics, etc. It is also used, in a more concise form, in the continuing education program designed for the practicing engineer who needs to learn more about this field. This labwork does, of course, require the students to apply the technical knowledge and skills they acquired during the course of their studies. But, most important, it makes demands on their ability to understand and learn new and difficult material fast since they are asked to devise the means, given the experimental set-ups and highly elaborate application softwares, to get the radiation pattern of an antenna from near field measurements. Indeed, our philosophy when developing the teaching material is based on the belief that students are best motivated when they are actively involved in the learning process. This approach, very much based on student-computer interaction, does allow a more clear idea of certain concepts that are hard to grasp using classical teaching methods: in fact, the computer provides, quickly and easily, a visual display of any operation or decision made, and hence, stimulates their curiosity and leads them to trying different things.

The relationship between computers and engineering education is usually a passionate one: it is either too much appreciated, or completely rejected. Nevertheless, when used as a learning tool, a computer can be a valuable help to both the instructor and the students, as long as first, it is not used as an end in itself, that is, for its own sake, and second, the final goal, that is teaching and learning, not forgotten. This implies that, in order to be effective, the application must run smoothly, in an easy and interactive manner, and must keep one's concentration on the specific problem to be studied, not on the programming details. Ease of communication, attractive interface and interaction, error-tolerance are therefore the qualities needed from the application: a well designed one, not only teaches the students, but also excites their curiosity.

This paper starts with a short technical presentation of near-to-far field transformation, followed with the description of the sequence of experiments designed to introduce students gradually to this field. Next, the experimental arrangements with both the hardwares and the softwares are presented, and finally the paper ends with the definition of the objectives of the study and the feedback we obtained from the students.

II. THEORETICAL AND TECHNICAL BACKGROUND

This section describes the background of the near-to-far field transformation in two different coordinate

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4 Supélec students graduate five years after high school.

systems, namely, the rectangular and the cylindrical systems. The reason is that a coordinate system is chosen to best fit the description of a certain type of measurement. A description in the rectangular coordinate system is hence used in the small anechoid chamber for classical measurements of antennas whose electric field can be described by separation of variables and the radiation pattern derived from the knowledge of the field along one axis, whereas the cylindrical coordinate system is used in the large anechoid chamber to describe more complex antennas whose radiation diagram cannot be derived in such an easy way, and indeed, the near field must be measured everywhere in space in order to perform a more complex transformation that will achieve the resulting pattern needed.

II.1. NEAR TO FAR FIELD TRANSFORMATION IN RECTANGULAR COORDINATES :

II.1.1. General case

The near to far field formulation is the result of combining the resolution of Helmholtz equation with the Fourier transform (FT) of the fields defined on a plane z = constant. A very simple relationship can be derived between two Fourier transforms ($\mathbb{F}$) on two different parallel planes:

$$\mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,z) = \mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,0)\exp(-jk_z z)$$

wherefrom one easily gets the electromagnetic fields everywhere, given measured fields at $z = 0$, i.e.,

$$\mathbf{E}(x,y,z) = \mathbb{F}^{-1}\left\{\mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,0)\exp(-jk_z z)\right\}$$

and hence, the radiation diagram by going to the limit ($r \longrightarrow \infty$) and using the stationary phase method:

$$\mathbf{E}(r,\theta,\phi) = jk_o \cos\theta \frac{\exp(-jk_o r)}{r} \mathbb{F}\{\mathbf{E}(x,y,z)\}(k_x,k_y,0)$$

$$\text{with } k_x = k_o \sin\theta \cos\phi \text{ and } k_y = k_o \sin\theta \sin\phi$$

Only the tangential components of the fields need be measured since the spectrum of the normal component of the fields at $z = 0$ can be derived in terms of the spectrum of the tangential components, using div $\mathbf{E} = 0$.

II.2. A special case: the variables can be separated in the aperture

The monomode horn antenna used for the first experiment on classical measurements is an example of this special case. The electric field radiated on the $z = 0$ plane can be written as:

$$\mathbf{E}(x,y,0) = g(x)\ f(y)\ \mathbf{e_x}$$

and the spectrum of this field is a simple product of the FT of each function separately, viz:

$$\mathbb{F}\{\mathbf{E}(x,y,0)\}(k_x,k_y) = \mathbb{F}\{g(x)\}(k_x)\ \ \mathbb{F}\{f(y)\}(k_y)\ \mathbf{e_x}$$

Then, from a measure along the y=0 line that gives $g(x)f(0)$, and another along $x = 0$ that gives $g(0)f(y)$, one can get $\mathbb{F}\{g(x)\}(k_x)f(0)$ and $\mathbb{F}\{f(y)\}(k_y)g(0)$. It is therefore possible to know the complete electromagnetic field everywhere in space, with only two one-dimensional measurements.

II.2. THE NEAR-TO-FAR FIELD TRANSFORMATION IN CYLINDRICAL COORDINATES

A 22 λ reflector antenna is used in this experiment where the measurements are fast as compared to the classical measurements case performed in a step-by-step fashion. Here, as will be described later on, the measurement of a hundred and twenty eight sampling points along the cylinder, in both polarisations, are performed in one step. Hence, the measurements needed everywhere in space before the radiation diagram can be derived take much less time. The far field will then be related to the Fourier transform of the near (measured) field through the following formulas:

$$E_\theta(r, \varphi, k_z) = -\sqrt{\frac{j}{\pi}}\,\frac{e^{-jkr}}{r}\sum_{n=-N/2+1}^{N/2} e^{jn\varphi}\left[\frac{\mathbb{F}\{E_z(n, k_z)\}}{\sin\theta\; g(a_n, \theta)}\right]$$

$$E_\varphi(r, \varphi, k_z) = -\sqrt{\frac{j}{\pi}}\,\frac{e^{-jkr}}{r}\sum_{n=-N/2+1}^{N/2} e^{jn\varphi}\left[\frac{\mathbb{F}\{E_\varphi(n, k_z)\}\sin\theta + \mathbb{F}\{E_z(n, k_z)\}\sin(a_n)\cos\theta}{\sin\theta\cos(a_n)\; g(a_n, \theta)}\right]$$

where

$$g(a_n, \theta) = \sqrt{\frac{2\pi}{k R_o \sin\theta\cos(a_n)}\, e^{jna_n}\, e^{-jk R_o \sin\theta\cos(a_n)}}$$

$$a_n = -\sin^{-1}\left(\frac{n}{k R_o \sin\theta}\right) \qquad N = 2ka \qquad k_z = k\cos\theta$$

Ro is the radius of the cylinder on the surface of which the measurements are performed, and a is the radius of the antenna. Since the antenna-probe distance is large compared to the wavelength, the Hankel functions that enter into the derivation are approximated using an asymptotical expantion.

III. THE SEQUENCE OF EXPERIMENTS

Two experiments in near-field antenna measurements were designed for graduating students, the first one introduces them to classical near-field antenna measurements, and the second presents them the state of the art in the field with the fast measurements experiment. Because of the very high level of sophistication needed to understand and perform this work, students are progressively introduced to this topic. A pre-requisite knowledge needed to learn and perform efficiently in this type of experiments, together with the specific difficulties led us to devise a whole set of experiments that would gradually give the students the necessary confidence in their knowledge. Hence, a nine weeks, five experiments labwork was designed, each session planned for a full four hour work, with a short presentation from the instructor.

First, they learn about modern antenna measurement methods through a bibliographical study based on classical as well as on the most recent published papers in the IEEE-AP or other such high level technical journal, under an instructor's guidance. We believe this is an important ingredient since it prepares the students to state of the art methods and equipment. It does also give them an appreciation of the objectives, and allows them to gain some confidence in order not to be overwhelmed by the setting and the hardware, or shy on using it.

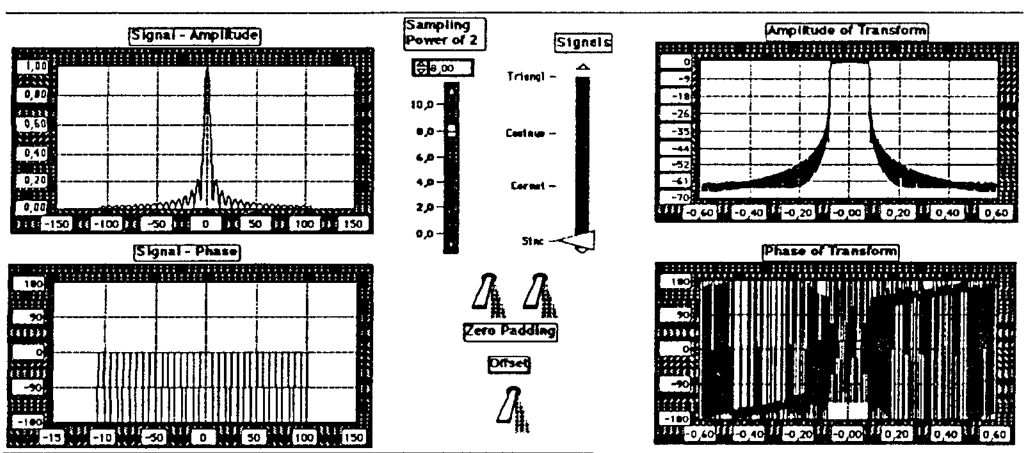

Figure 1: The FFT instrument front panel

They then learn to make measurements with the HP 8720 vector network analyser and the handling of the FFT, both for later use. Indeed, to give them a feeling of the problems associated with those types of measurements, a "hands-on experiment" on the FFT was needed. The reason for this experiment is the following: students are usually taught Fourier Transform principles early in their engineering education life, but this knowledge remains theoretical since students are not usually expected to do more than solving exercises. Indeed, they are seldom asked to choose parameters, make the necessary trade-offs or find the best compromise that would achieve a specific requirement. They do not therefore see the consequences of the various choices they make and, hence, miss the opportunity to gain an insight into the actual handling of this tool. We therefore designed an "instrument" (Fig. 1) to simulate the FFT using a Macintosh computer and Labview (LV), a commercially available software from National Instruments[1]. This experiment is actually an attempt to make a personal computer part of teaching, and its purpose is to clarify certain concepts such as sampling, truncation, zero-padding, etc, that are hard to grasp using classical teaching methods.

The FFT session starts with a short hands-on instructor's presentation, first of the theory behind the FFT using a small Hypercard program, then of the software they will be using. Next, in a group of two or three, they perform the experiment by themselves. A student is in constant control of the program, and hence, is free to try any possibility available. Our choice of software was based on the premice that technical knowledge through simulation procedures and equipment can work only when students' attention is focused on the specific technical aspect to be learned, with none of the frustrations connected with bad instrumentation or difficulties with the software. Next, the two experiments in near-field antenna measurements are performed.

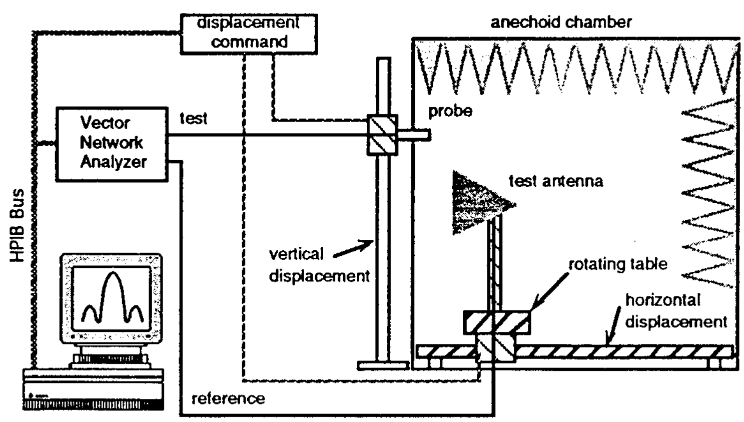

Figure 2: The classical measurement method experimental set-up

IV. EXPERIMENTAL SET-UPS

IV.1. CLASSICAL MEASUREMENTS

IV.1.1. The Hardware

All the measurements are performed in a cubic anechoid chamber, 2.5 m per edge. The absorbing material on the walls are of the APM20 type from Hyfral (reflectivity of -50 dB at 10 GHz).
Three mechanical displacements are used in the experiment:

- rotation of the test antenna positioned at the center of a rotating table,
- translation of the the measuring probe along a vertical axis,
- translation along a horizontal axis for varying the distance between the antenna and the probe

Working frequency is 10 GHz, the tested 20 dB-horn antenna is the emitter, an X band rectangular waveguide probe is the receiver, and the emitter-receiver system is an HP 8720B vector network analyzer. A very low noise preamplifier greatly improves the signal-to-noise ratio of the measurements. A rotating joint allows the tested antenna to be freely linked to the rest of the system and a high performance cable follows the vertical motion of the probe.
A Macintosh IIx controls the whole system, including the network analyzer and the displacements,

[5] More on the software in section IV.2.2.

with an HPIB board giving access to an IEEE-488 bus.

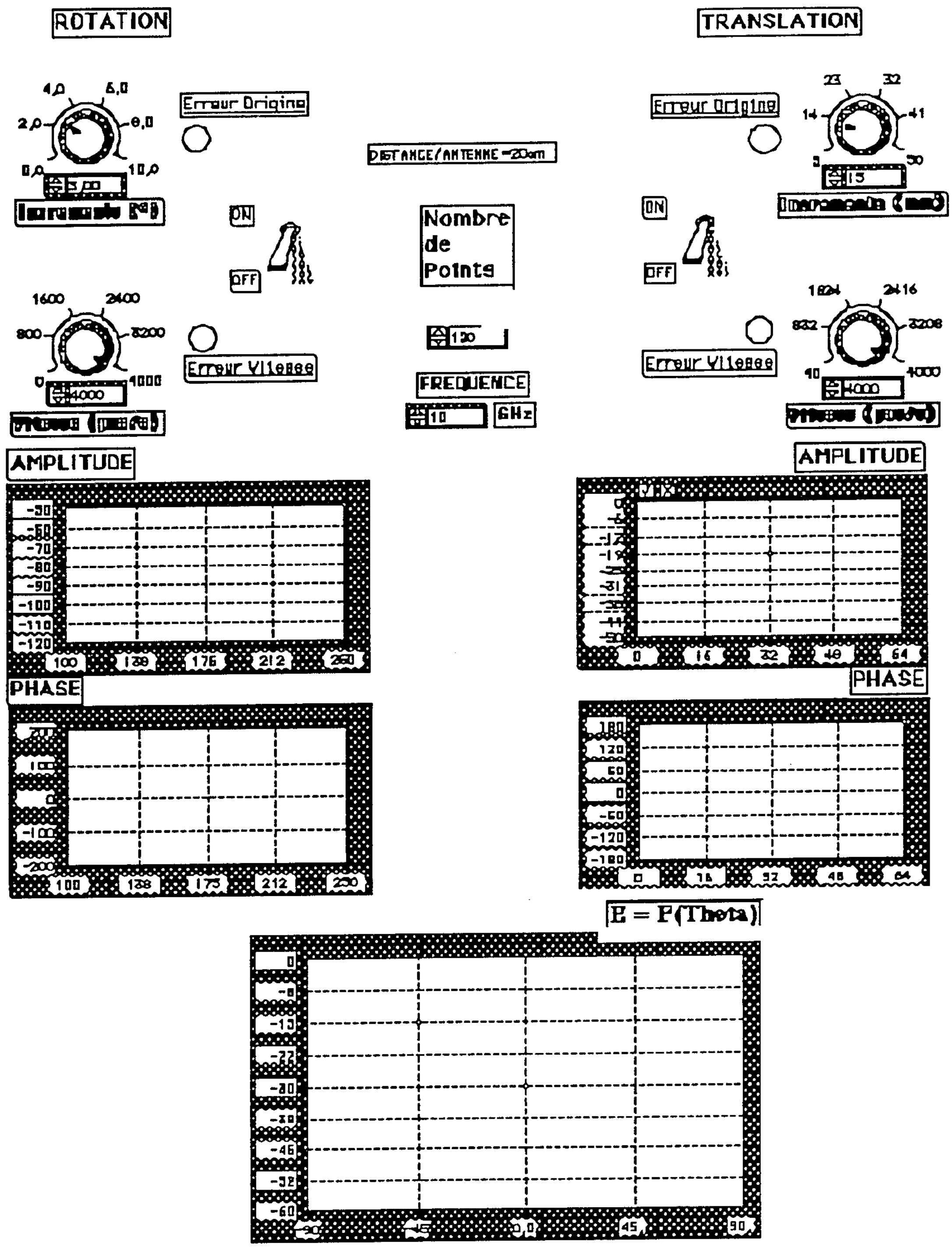

Figure 3: The classical measurements front panel

IV.2.2. The software

It is well known that Macintosh software is hard to write, and the purpose of the work is not programming anyway. Supelec students in their final year have different backgrounds and know different programming languages. What is needed therefore is a programming environment for

people who are not professional developers. Labview (LV) provides such an environment in a graphical interface that "is the easiest icon-based programming system available".
LV is a complete instrumentation software system for data acquisition, instruments control, data analysis, DSP, graphing and data presentation: it calls on the concept of a VI (Virtual Instrument), a software file that looks and acts like a real lab instrument on screen. Users graphically build software modules called virtual instruments (VIs) that look and act like real lab instruments on screen. Each VI is made of two parts: the front panel (Fig. 2) and the block diagram. The front panel is custom designed by the programmer for the specific application, whereas the block diagram is the program itself. A program is built by wiring together two black boxes. No distinction is made between a VI and an operation, both are black boxes. By connecting the icons for these modular VIs in a block diagram, you can easily create, modify, combine and exchange VIs to form more sophisticated VIs. One can create software instruments quickly and easily in this clear, graphic environment, without any prior knowledge whatsoever of a programming language. LV includes a library of instruments to drive laboratory equipment and retrieve measurement data while at the same time controlling the data acquisition boards. It also includes a compiler: block diagrams are automatically compiled upon execution, so it runs fast, just as any program written in a high level programming language. It is very tolerant on errors and has built-in trouble shooting features. This environment is definitely superior for developing education software, both in time savings and in bug avoidance.

The VI concept was used to design an "instrument" on a Macintosh computer to drive all of the experiment [6]. The application runs smoothly, in an easy and interactive manner, and keeps the focus on the specific problem to be studied, not on programming details: students are safely preserved from frustrating situations having to do with difficulties with the software rather than with the actual contents or material to learn, which is the reason why the application was designed in this environment in the first place.

IV.2. FAST MEASUREMENTS

IV.2.1. The Hardware

The experimental set-up (Fig. 5) allows measurements in cylindrical coordinates to be performed, in two orthogonal polarisations, for the 2-to-8 GHz frequency range. It makes use of the modulated scattering technique (Fig. 4) which works as follows.

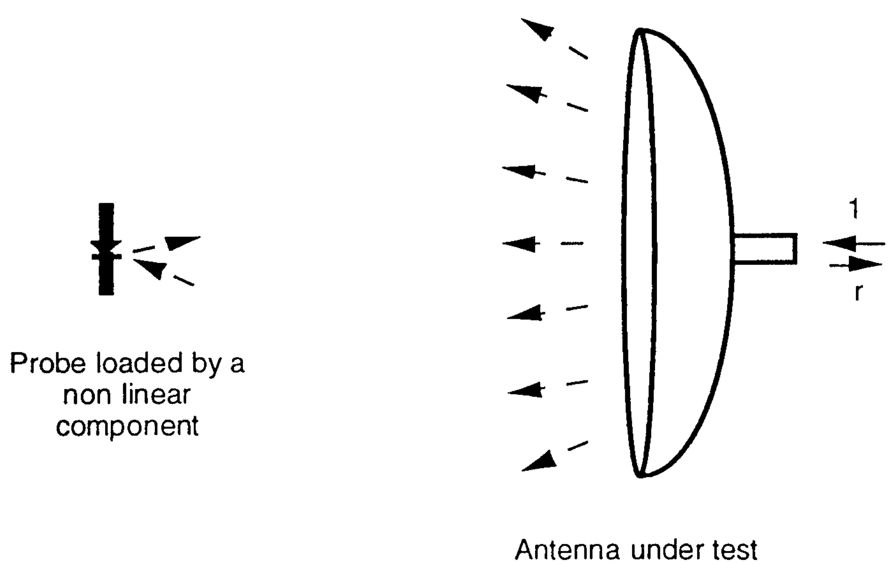

Fig. 4: The modulated scattering technique illustration

Introducing a probe into the field of the antenna under test modifies its adaptation, i.e., the field scattered towards the antenna. The reflection coeficient of the probe is a measure of the field radiated

[6] Another different instrument was built for the FFT experiment.

by the antenna. Therefore, one does not need any microwave access to the probe in order to measure this field. Furthermore, when loading the probe with a non linear component, a modulation of this component allows tthe contribution of the probe to the scattered field to be identified. This technique can be adapted to a whole array of probes for near field antenna measurement by using a multiplexer to modulate each probe sequentially.
The whole system, made up of mecanical components (motors permitting displacements in all directions), microwave probes and other electronic components (such as a microwave source, multiplexers, etc) is driven automatically by a Macintosh II Fx computer with an IEEE-488 expansion board. The antenna is mounted on a turntable which can rotate around a vertical axis; the turntable itself can be displaced horizontally in order to be able to change the antenna-probes distance. Probes are positionned along a vertical line. As the antenna rotates, measurements are performed by the probes at set discrete angles: measurements are therefore equivalent to field sampling along the φ-axis, whereas measurements performed by the 128 probes on the vertical line are equivalent to field sampling along the z-axis. The measured field is radiated towards a secondary antenna made up of a pillbox antenna and an elliptic-cylindrical reflector strongly coupled to the probes. The probes are considered to be ideal dipoles, an acceptable simplification for the very thin short wires used. They are excited sequentially.
The microwave signal is supplied by a YIG source. The measured signal is modulated by the low frequency signal: hence, the spectrum of the measured signal is a two lines spectrum at equal distance from the microwave line. These two lines are then extracted and transformed trough a double low frequency receiver into a dc signal.
The measurement on the complete cylinder of a 22 λ antenna is completed in about 15 s.

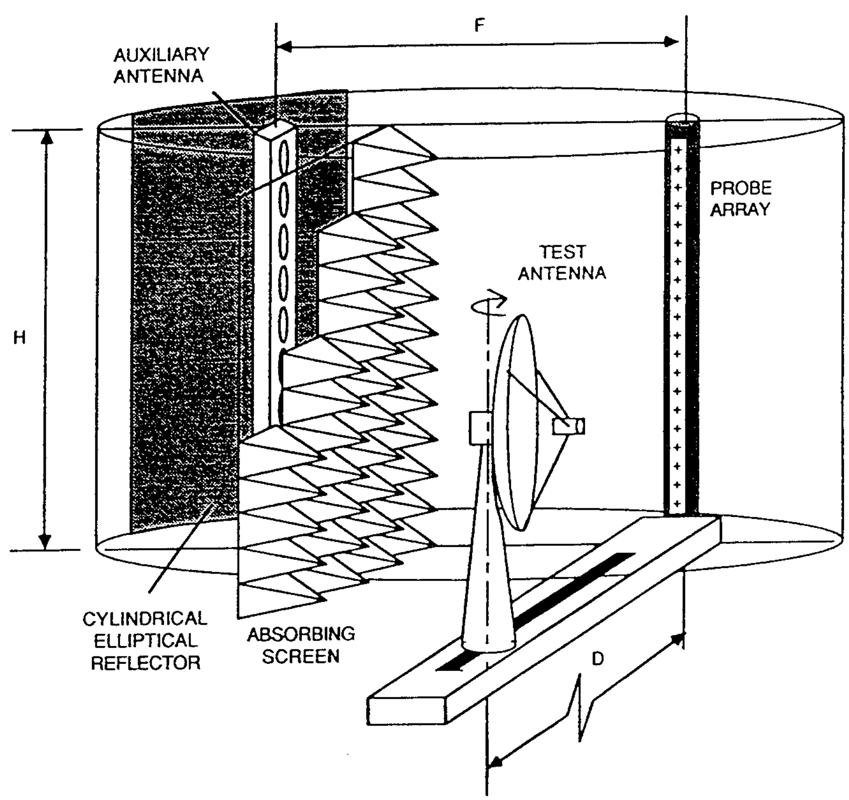

Fig. 4: The fast measurement method experimental set-up

IV.2.1. The Software

Unfortunately, LV is inadequat for this type of programming because of the complexity of the experimental set-up, and also because speed is of utmost importance. We are therefore in the

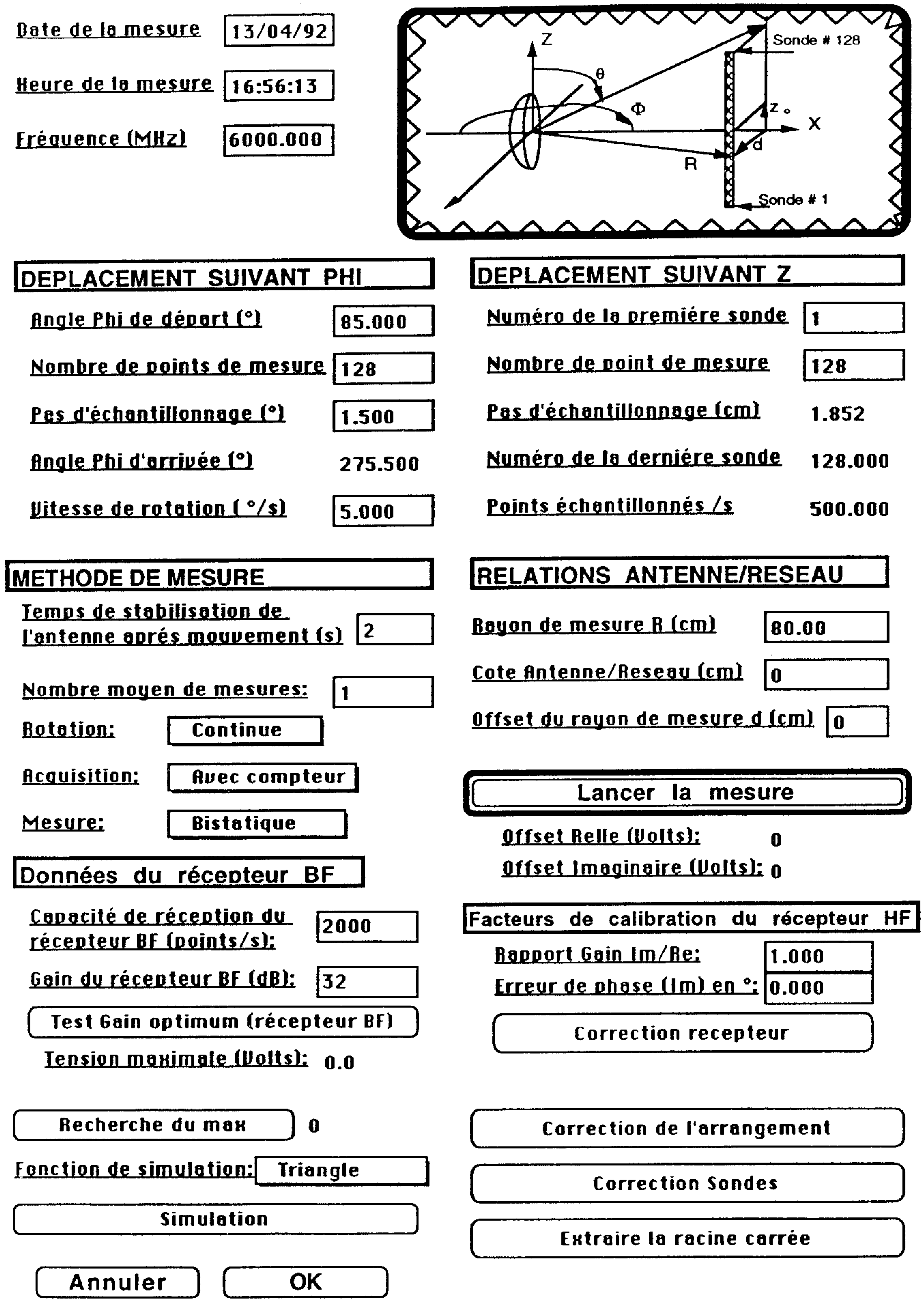

Figure 5: The fast measurement front panel

obligation to do our own programming. This is not the easiest thing to do on a Macintosh computer, but we do have tools to help, especially Apple's programming environment MPW. The end product, however, must be transparent to the user.

MPW includes several handy features relevant to our needs:

* The possibility of mixing programming languages: it includes a Pascal, a C, an Assembly language compilers, and is compatible with Language Systems' Fortran. Hence, all the hardware drivers routines are written in C, all computation routines are written in Fortran, and the expansion boards are programmed in Assembly Language. The Pascal language is used with Apple's own system library MacApp.

* The advantage of using MacApp library is two-fold: first, it insures that the application being written will be compatible with future versions of the operating system; and second, since it is object oriented, it saves time by allowing a great speed of programming.

Figure 6 illustrates the main dialog window available to the user for the fast measurement technique. All the commands are available at the touch of a button, all the parameters can be entered through this window, and the whole system, remotely driven from this "terminal", is transparent to the user. Errors and/or mistakes in choosing parameters are handled by the software perfectly, in the sense that the system does not crash but displays the type of error done; the user then has the choice of keeping the default value or entering a new one. For example, a choice of a frequency outside of the microwave source range brings automatically up a warning window that must be aknowledged before being able to change the value of this parameter to a permissible one. Also, trying to run the application from this window will bring up a sequence of warning windows, prompting the user to acknowledge the various default values of the parameters or to change them.

The application offers the user the possibility to perform all measurements that can be performed with the type of equipment available. Displacements of the antenna are possible in the φ direction, starting and ending at any angle, in any number of steps, in any rotation speed (unreasonable values will bring up the warning window), continuously or in steps; along the vertical axis (the x-axis), the choice of the first and the last probes, of the sampling speed, and of the polarisation to be measured (either one or both) are given; the distance between the probes and the antenna along the horizontal z-axis (the radius of the cylinder) can also be chosen. The measure can be performed in a monostatic or in a bistatic fashion.

Once the measure of the near field is completed, one can proceed to take into account the errors inherent to the equipment: the necessary corrections that can be performed on the measured field include those due to differences in the gain and in the phase of the two channels (one for the real part, and the other for the imaginary part) microwave receiver, those due to the probes (different probes may have different radiation diagrams), etc. In case measurements are done in bistatic, we must include the correction due to the arrangement in order to extract the contribution of the auxilliary antenna-probes path. All these corrections are obtained through other measurements and can be performed before or after measuring the field.

The results are presented in a double entry table, one entry is φ, the other is θ. Any component of the field can be graphically displayed as a function of one of the variables, the other variable been fixed. Finally, a near-to-far field transformation is performed on this measured field, whether corrected or not, and the radiation diagram is derived. A 128x128 points calculation takes about 40s for the spectrum and about 10s for the far field.

V. Objectives and Feedback

The goal of the experiment is to give students access to a highly sophisticated and not very intuitive measurement method. Students are asked to use the near-to-far field transformation technique to the horn antenna described in the foregoing, and develop the necessary experimental and algorithmic procedures to obtain the radiation pattern of the given antenna. Students are therefore faced with all the electromagnetic difficulties inherent to this technique and must use their skills to understand and solve them. On the other hand, the necessary but secondary activity of programming which usually requires the mastering of both a high level programming language and the operating system, does not take much of their time.

It is well known that Macintosh software is hard to write, but the purpose of the work is not programming anyway. A programming environment for people who are not professional developers is provided by LV in a graphical interface that "is the easiest icon-based programming system available" with access to all the functionalities available in the system. It calls on the concept of a VI which does make things simple since no prior knowledge of programming is necessary. It is then possible to get students with different programming backgrounds work together efficiently.

A VI for data acquisition was developed to drive the measurements which are subsequently saved in a file. Students must then develop another VI that reads the data file, processes the data, and write the results in a results file. During this phase of the work, the programming itself takes no time compared to the thinking and understanding work students have to perform. Indeed, the near-to-far field transformation, data sampling, and the FFT techniques have now to be used for a real world application. During this phase, they do better understand the difficult concept of evanescent waves, and of the visible and invisible plane wave spectra of an antenna.

Next, the students must get the necessary data for later processing. They see the difficulties associated with electromagnetic field measurements, the choice of the absorbing material, the problems with propagation in the cables and the signal-to-noise ratio. Choosing different sampling rates, varying the antenna-probe distance, and trying combinations of these make students appreciate the consequences on the resulting radiation pattern of these parameters. They can finally have an experimental proof of the validity of the technique used by measuring directly the far field by positioning the antenna far away from the probe.

This advanced labwork is highly sophisticated as compared to other types of experiments for students: indeed, it does not introduce students to electrical engineering basics or fundamentals, as is usually the case, but to a more specialized and narrow knowledge that makes demands on their technical knowledge and skills they acquired during the course of their studies. Most important, this labwork requires them to devise the procedure to follow: students are usually asked to measure one thing or another, plot the results, and comment on these. Here, we do not ask them to make measurements. Instead, we ask them to find the best possible way to approach the results they are able to derive analytically, and leave them free to choose any procedure, within the limits of what can safely be done, to achieve this requirement. Students learn by doing and, if the principles are well chosen, the simulation acts exactly like the real thing, and new things can be tried.

Have we achieved our goals? To answer this question, we have two possible feedbacks: one of course comes from the students themselves, and the other one from the way they approach and perform in the next experiments and their understanding in applying the concepts they have just learned.

The reaction of the students has been very positive. They did find the tool very convenient, especially for visualizing almost instantly the consequence of choices they make. A bad result does actually make them eager to find and understand the reasons for that, and leads them to try other parameters and/or possibilities. Finding the correct answer does not seem sufficient since they do look for the reasons why this answer is correct and that one was not. When a bad result is due to the misunderstanding of a concept and this has been corrected, it is almost sure that a misconception based on this concept can no more take place. For example, they now know, and will probably not forget, that the application of the zero-padding concept to a function in order to improve its spectral resolution cannot be done systematically and can actually deteriorate what they are trying to improve. From their point of view, the experiment should include more material. We can actually go a step further and include the VI's of filters and windows into the main instrument instead of keeping them separate. There is a continuing evolution of this application, but it takes time to develop a potent, yet friendly, useful educational tool. We hence decided on involving the students more deeply into developing and/or improving on these tools, and the first experience with this approach has been encouraging, and is reported elsewhere. As R.S. Wolff said, we are moving towards the age of "knowledge navigation", and the first thing is to be able to navigate.

VI. CONCLUSION

Although this experiment is very sophisticated and uses very elaborate equipment, students were very rapidly at ease with it. They actually learned very much from it in a short amount of time, giving them

a clear picture of both the electromagnetics theoretical and experimental aspects of antenna measurements. This experiment is in constant evolution based both on new possibilities to be tried and on student's comments.

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COMPUTER-BASED ELECTROMAGNETIC EDUCATION

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ABSTRACT

Computers provide an exciting opportunity for boosting electromagnetic education and corporate training. Animated graphics of the wave propagation phenomenon, visualization of the abstract and highly mathematical subjects, one-on-one and self-paced tutoring, and the ability to mimic often unavailable and expensive laboratory experiments are among the often-cited benefits of a computer-based electromagnetic education. In this paper, we review the activities of the NSF/IEEE Center for Computer Applications in Electromagnetic Education (CAEME). This Center was established to stimulate and accelerate the use of computers and software tools in EM education. A reflection on the extensive software package developed and distributed by the CAEME Center is described and examples of the developed software are presented. To help integrate available EM software in classroom teaching and corporate training, CAEME developed four multimedia lessons for instruction. These interactive media lessons integrate and allow individuals to interactively manipulate information from multimedia sources such as video, software, and animated graphics and also include instructional information such as quizzes and tutorials to help evaluate the students' performance. Features of these lessons are presented, and future developments in the Center's activities are described.

I. INTRODUCTION

The use of computers and software tools in science and engineering education is no longer an opportunity but a necessity that may help address some of the challenges facing education in the nineties and beyond. With congested curricula, there is a serious need to effectively and quickly teach abstract and highly mathematical subjects, and with the prohibitively expensive modern laboratories, the use of computers and software simulation tools is becoming an integral part of modern curriculum development. For example, well-structured software tools may provide adequate visualization capabilities that may help communicate abstract subjects and present dynamic phenomena such as wave propagation, reflections, and interferences. Furthermore, computers provide one-on-one tutoring for subjects that require long learning time and may help in simulating open-ended problems that mimic laboratory experiments. Computers may also provide the ability to simulate practical engineering design problems that motivate students and stimulate discussion of exciting practical engineering applications.

Many educators are aware of the challenges and opportunities presented with the proliferation of computers on university campuses. New courses have been developed, software and computer-generated movies have been created [1], and some efforts have been initiated to develop a computer-based curriculum in electromagnetics. However, many of these activities are hindered by the lack of effective distribution mechanisms to

facilitate sharing and minimize duplication, and by the nonexistence of standards for software development and documentation.

The National Science Foundation/Institute of Electrical and Electronics Engineers (NSF/IEEE) Center for Computer Applications in Electromagnetic Education (CAEME) was established as a result of a grant from NSF to IEEE on behalf of the Antennas and Propagation Society (AP-S). CAEME's objective is to stimulate and accelerate the use of computers and software tools to help boost electromagnetic education. Electromagnetics is often perceived as an abstract, highly mathematical, and difficult subject to understand and comprehend. Computer visualization and animation capabilities, therefore, are expected to be of significant value in teaching electromagnetics. The CAEME Center is expected to play a leadership role not only in the development and distribution of software but also in providing a focus for future software development and avenues for software integration in classroom teaching. CAEME proceeded to achieve its objectives by:

a. publishing a catalog of available EM educational software

b. providing seed money from NSF funding to help develop new software for EM education

c. holding workshops and special sessions in conjunction with international symposia on "Innovative Applications of Computers in Electromagnetic Education"

d. serving as a focus for distribution of its software and video products using the National Electrical Engineering Department Heads Association (NEEDHA) mailing list, and

e. initiating a strong fundraising effort so that the Center will continue to be active and self supporting after the three years of NSF funding.

This article summarizes the activities of the CAEME Center and describes examples of its software development projects. Reflections on the *CAEME Software Book*, Vol. I [2, 3], will be highlighted and future software development projects will be listed.

As instructors continue to integrate computers and software tools in classroom teaching, more and more of the limitations of using this technology in education are being realized. For example, it is not clear if students will effectively and independently be able to understand basic phenomena from the numeric or graphic representations of the output of simulations. Also, avenues for the effective integration of simulation, demonstration, and computer-based homework assignments and tests in and outside of a typical classroom teaching procedure are not clearly defined. Many courses need to be restructured, and even the role of the university professor needs to be redefined to fit the era of a computer-based curriculum.

Fortunately, this uncertainty in understanding the role of computers and software tools in engineering education has coincided with rapid growth in the area of multimedia presentations [4, 5]. Interactive video applications integrate the visual power of video, interactivity of software, and an ability to structure educational lessons that include tutorials, quizzes, and maintenance of scores for the instructor's use. To help integrate software in EM education, CAEME developed four multimedia lessons in electromagnetics. The features of these lessons are described and the fact that the use of multimedia technology may make teaching electromagnetics fun, visual, effective, and, most importantly, independently understandable by students is also demonstrated.

II. THE CAEME CENTER -- ORGANIZATIONAL STRUCTURE AND SUMMARY OF ACTIVITIES

A. Organizational Structure of CAEME

The Center for Computer Applications in Electromagnetic Education is funded by a grant from the Undergraduate Science, Engineering, and Mathematics Division of the NSF. The grant was made to and hence is managed by the Executive Office of IEEE on behalf of the Antennas and Propagation Society, which arranged for the preparation of the CAEME proposal. Having CAEME under the umbrella of IEEE provides a broad base for participation by professional societies, universities, and corporate sponsorship by industry [3].

The CAEME activities, however, are controlled by a policy board that includes representatives from IEEE, NSF, participating professional societies, sponsoring companies, and the CAEME director. The policy board meets twice per year to monitor the CAEME budget and activities, and to approve funding for new software development projects at various institutions. Policies regarding international participation, copyrights, and licensing of the CAEME books are discussed and approved by the policy board. The policy board also decided to establish a group of technical advisors chaired by Professor Robert E. Collin of Case Western Reserve University to assist in evaluating CAEME's technical activities and products. During the three-year NSF funding, the policy board is chaired by the president of the Antennas and Propagation Society.

B. Summary of CAEME Activities

During the three-year NSF funding, CAEME focused its activities on creating software suitable for undergraduate EM education. To date, CAEME has available and/or under subcontract software development projects that cover all aspects of an introductory course in electromagnetics. Although it was not part of the original NSF proposal, CAEME has recently devoted significant efforts to help promote the use of computers and software tools in classroom teaching. Specific examples of this activity include the creation of four multimedia lessons on introduction EM and the publication of a new journal [6] that deals with various aspects of computer applications in engineering education. The following is a summary of CAEME activities:

1. Published a catalog of available software for EM education. The catalog lists various software packages, their availability, cost, and an example of their use. Copies of this catalog are available from the CAEME Center.

2. Organized several workshops and special sessions in conjunction with the IEEE AP-S International Symposium, the IEEE MTT-S Microwave Symposium, the Applied Computational Electromagnetic Society (ACES) Conference, the Progress in Electromagnetic Research Symposium (PIERS), and the American Society of Engineering Education (ASEE) Conference. During the first two years of CAEME operation, the workshops were focused on describing the features and training the participants on the use of available software tools, particularly those developed by CAEME faculty. More recently, CAEME used these opportunities to discuss ways and means of promoting the integration of software tools in EM education.

3. Funding of software development projects. In three years of operation, CAEME funded 27 software development projects at 18 universities. Tables 1, 2, and 3

list the CAEME projects. In addition, colleagues from MIT [7], Georgia Tech [8], Naval Postgraduate School [9], and Lockheed Corporation [10] participated in CAEME projects at no cost. It is truly remarkable to see educators from universities across the country collaborate and participate in this unique effort that will certainly have a lasting impact on EM education.

4. Published the first software book in September 1991. Copies of the book were distributed to over 250 universities in the United States and 23 foreign countries. In many cases, universities paid a $500 two-year membership fee to join the CAEME Center, while in a few others, single copies were provided to individual faculty members at cost ($150). A more detailed description of the features of the CAEME book will be given in following sections.

5. To help promote the integration of software tools in classroom teaching, CAEME developed four multimedia lessons. These lessons combine multimedia information from simulation, video, and animated graphics with instructional information such as tutorials and quizzes. The four developed lessons are on electromagnetic waves, electrostatic charges and Coulomb's law, conducting and dielectric materials, and a review game lesson on electromagnetics called Tic-Tac-Toe. Features of these multimedia lessons will be described in more detail in Section V.

6. As CAEME intends to continue to be active and self supporting after the three years of NSF funding, an important aspect of its activities was to raise funds from corporate sponsors and charge a membership fee to participating professional societies. To date, CAEME has corporate sponsorship from Hewlett-Packard, Texas Instruments, Lockheed Corporation, Andrew Corporation, and Motorola. Participating professional societies include IEEE AP-S (host), IEEE MTT-S, IEEE EMC-S, and the Applied Computational Electromagnetic Society (ACES). More than $180,000 has been raised thus far, which is sufficient to support CAEME for two years after the NSF funding. This is based on the present level of activities, but clearly more funds are needed to adequately address CAEME's expanded activities in areas such as the development of multimedia lessons and the use of CD-ROM technology to distribute CAEME products.

III. *CAEME SOFTWARE BOOK*, VOL. I

As a result of the software developed using CAEME seed funding in 1990, as well as because of other software and videos contributed to the Center, the first CAEME software book was published in 1991 after only 18 months of the Center's operation [2]. The book contains sixteen chapters, fifteen $3\frac{1}{2}$ diskettes, and two VHS videos. Fifteen chapters are associated with the developed software and the other discusses the experimental demonstrations for teaching electromagnetic fields and energy developed by Professor M. Zahn and colleagues at the Massachusetts Institute of Technology (MIT) [11].

A. Reflections on the *CAEME Software Book*

Examination of the contents in Table 4 shows that the book provides broad and comprehensive coverage of an introductory course in electromagnetics. It includes both tutorial and simulation software in topics such as vector algebra, Maxwell's equations,

Table 1. List of EM software development projects funded by CAEME in 1990.

Project	Principal Investigator	Institution
1. MacEM	K. Lonngren	University of Iowa
2. Lienard-Wiechert Field Generator and Hypercard Tutorial for Visual EM	R. Cole	University of California, Davis
3. Preparation of Computer-Aided Instructional Materials for Teaching Undergraduate EM: Integral Equations and Numerical Solution Methods	C. Butler and D. Wilton	Clemson University University of Houston
4. An Interactive Software Package for Teaching a Course on Computational EM	M. Iskander and O. Andrade	University of Utah
5. An Interactive Menu-Driven Software Package to Solve Static, Sinusoidal Steady-State, and Transient 2D EM Problems	J. Lebaric	Rose-Hulman
6. Simulator for Signal Propagation on General Multiconductor Transmission Lines	L. Carin	Polytechnic University
7. Electromagnetic Waves: A Software Package	W. Stutzman	Virginia Polytechnic Institute
8. Nuline: A Time- and Frequency-Domain Transmission Line Analysis Program	F. Tesche	Tesche Associates
9. Computer-Aided Instruction for Theory and Design of Linear Antenna Arrays	S. Blank and S. Wang	New York Institute of Technology
10. Analysis of TE and TM Modes in Arbitrarily Shaped Waveguide Structures Using Finite-Difference and Conjugate-Gradient Method	T. Sarkar	Syracuse University
11. 3D: A Software Package Providing Three-Dimensional Antenna and EM Field Displays on Personal Computers	J. McKeeman	Virginia Polytechnic Institute
12. Analysis and Visualization of EM Fields in Cylindrical Waveguides	A. Elsherbeni	University of Mississippi

Table 2. List of EM software development projects funded by CAEME in 1991.

Project	Principal Investigator	Institution
1. 2-D Static and Dynamic Software	J. Lebaric	Rose-Hulman Institute of Technology
2. Analysis and Visualization of EM Waves Inside Waveguides and Cavities	A. Elsherbeni	University of Mississippi
3. An Array Antenna Pattern Program	W. Stutzman	Virginia Polytechnic Institute
4. Simulation of EM Phenomena Using Field Line Animation	P. Visscher	University of Alabama
5. Field Generator for Electromagnetic Scattering	R. Cole	University of California, Davis
6. Computer Graphics Aided Teaching and Learning Tools for Antennas	S. Chakrabarti	University of Kansas
7. Antenna Pattern Visualizating using Personal Computers	A. Gasiewski	Georgia Institute of Technology
8. Development of an Interactive Video Educational Software Using QUEST	M. Iskander	University of Utah

Table 3. List of EM software development projects funded by CAEME in 1992.

Project	Principal Investigator	Institution
1. Interactive Exercises for Visual Electromagnetics	R. Cole	University of California, Davis
2. Development of a PC-Based Simulation of Electromagnetic Wave Propagation	T. Kao	Loyola-Marymount University
3. Radiation Characteristics of Phased Array Antennas and Mutual Coupling of Microstrip Antennas	A. Kishk	University of Mississippi
4. Application of the Finite Element Method for Quasi-Static and Dynamic Analysis of 2D Arbitrarily Shaped Inhomogeneous Anisotropic Multiconductor and Multidielectric Waveguiding Structures Utilizing the Classical Elements and Edge Elements	M. Salazar-Palma	Polytechnic University of Madrid
5. Reflector Antenna Analysis Software: An Educational Approach	Y. Rahmat-Samii	University of California, Los Angeles
6. Analysis and Design of Antenna Arrays	A. Elsherbeni	University of Mississippi
7. Use of Matlab to Solve EM Problems	J. Lebaric	Rose-Hulman Institute of Technology
8. Development of Interactive Video Lessons	M. Iskander	University of Utah

Table 4. Contents of the first CAEME software book.

A. Software for Fundamentals of Electromagnetics

Chapter 1 --	Fields & Operators; M. Lapidus, Lascaux Graphics
Chapter 2 --	Elements of Engineering Electromagnetics; N. N. Rao, University of Illinois
Chapter 3 --	ElectroCard and SilverHammer: Teaching Fundamentals of Electromagnetics; R. Cole, D. Krull, M. Sweitzer, S. Finch, and T. Palmer, University of California, Davis
Chapter 4 --	MacEM; K. E. Lonngren and W. B. Lim, University of Iowa
Chapter 5 --	Electromagnetic Waves -- A Video Tutor Graphics Package; W. L. Stutzman and A. B. Garrett with code modifications by M. Cerny, Virginia Polytechnic Institute and State University
Chapter 6 --	Electromagnetic Software for Solving Static and Dynamic 2-D Field Problems on a Personal Computer; M. Melton, J. Engel, and J. Lebaric, Rose-Hulman Institute of Technology
Chapter 7 --	Experimental Demonstrations for Teaching Electromagnetic Fields and Energy; M. Zahn, J. R. Melcher, and H. A. Haus, Massachusetts Institute of Technology

B. Software for Transmission Lines

Chapter 8 --	Nuline Transmission Line Analysis Program; F. M. Tesche, Tesche Associates, Dallas, Texas
Chapter 9 --	Polylines: A Multiconductor Transmission Line Simulator; L. Carin, M. Giordono, and J. Beninati, Polytechnic University of New York

C. Software for Waveguides

Chapter 10 --	Mapping of Vector Fields Inside Waveguides; A. Z. Elsherbeni, D. Kajfez, and J. A. Hawes, University of Mississippi
Chapter 11 --	Analysis of Waveguides Using the Conjugate Gradient Method; V. Narayanan and T. K. Sarkar, Syracuse University

D. Software for Antennas and Radiation

Chapter 12 --	Computer-Aided Instruction for Linear Antenna Array Theory and Design; S. J. Blank and S. L. Wang, New York Institute of Technology
Chapter 13 --	An Interactive Graphics Tool for Displaying Three-Dimensional Equations; J. C. McKeeman, G. M. Ruhlmann, and M. A. Colbert, Virginia Polytechnic Institute and State University
Chapter 14 --	"Mininec," Containing Mininec 3.13 and Graps 2.0; R. W. Adler, naval Postgraduate School

E. Software for Numerical Techniques

Chapter 15 --	Computational Electromagnetics -- Software for an Introductory Course; M. F. Iskander and O. M. Andrade, University of Utah
Chapter 16 --	Simulation of Electromagnetic Phenomena Using a Finite Difference-Time Domain Technique; K. Li, M. A. Tassoudji, R. T. Shin, and J. A. Kong, Massachusetts Institute of Technology

electro- and magnetostatics, transient and sinusoidal steady-state analysis of transmission lines, display of field configurations associated with modes in waveguides of regular cross sections, analysis of wire antennas, and an introduction to numerical techniques, including the Finite-Difference Time-Domain method and the method of moments. Specific examples of the software will be discussed later, but it may be worth mentioning that all the software packages are interactive and menu driven, and provide both simulation and visualization capabilities. It is believed that an easy-to-use I/O interface is crucial to the successful use of software in teaching and corporate training.

B. Examples of Software Packages

Examples of the software packages available in the first CAEME book are available in several publications [3, 7, 12, 13]. In this paper, focus will be placed on software packages that address issues of interest to the MTT community.

1. Simulation of electromagnetic phenomena using a Finite-Difference Time-Domain (FDTD) technique

This is a 2D FDTD program with movie-making capabilities [7]. The electric- and magnetic-field results are solved as a function of time and stored solutions of scattering or radiation problems are then visualized in a movie format. Dielectric, magnetic, or conducting materials may be used to construct the object of interest. Sinusoidal or Gaussian beam plane waves, or line sources may be used as excitation sources. Both TE and TM polarizations are analyzed. In addition to the capability of animating the propagation of the EM fields, radiation and scattering patterns can be generated. An example of an animated series which shows the focusing action of a dielectric lens when excited by a sinusoidal plane wave is shown in Fig. 1. The software operates on IBM 386-type PCs and requires a math coprocessor.

2. Transmission line simulators

There are two software packages for transmission-line analysis. The first [14] is suitable for determining the time-domain or sinusoidal steady-state response of a single-conductor transmission line over a perfectly conducting or a lossy return ground plane. Each end of the line may be terminated by a general series R, L, C impedance, and excitation may be lumped voltage source, current source, or an incident plane wave. This software package is menu driven and easy to use. It also has an attractive graphics package for plotting the output results. Figure 2 shows the output voltage versus time at an open-circuit load for both cases of perfectly conducting and lossy ground planes. The pulse distortion as a result of the losses on the ground plane is clearly demonstrated in Fig. 2b.

The other transmission-line analysis software package is Polylines [15]. This software provides a frequency-dependent analysis of a signal propagating on single or coupled transmission lines. Parameters such as the characteristic impedance, effective dielectric constant, phase velocity, and cross talk as a function of frequency are typical outputs of this program. Figure 3 shows the variation of the characteristic impedance of a microstripline as a function of frequency, while Fig. 4 shows a comparison of the output voltage versus time when dispersion is not taken (Fig. 4a) and is taken (Fig. 4b) into account. The above results show both the frequency and time domain capabilities of Polylines [15].

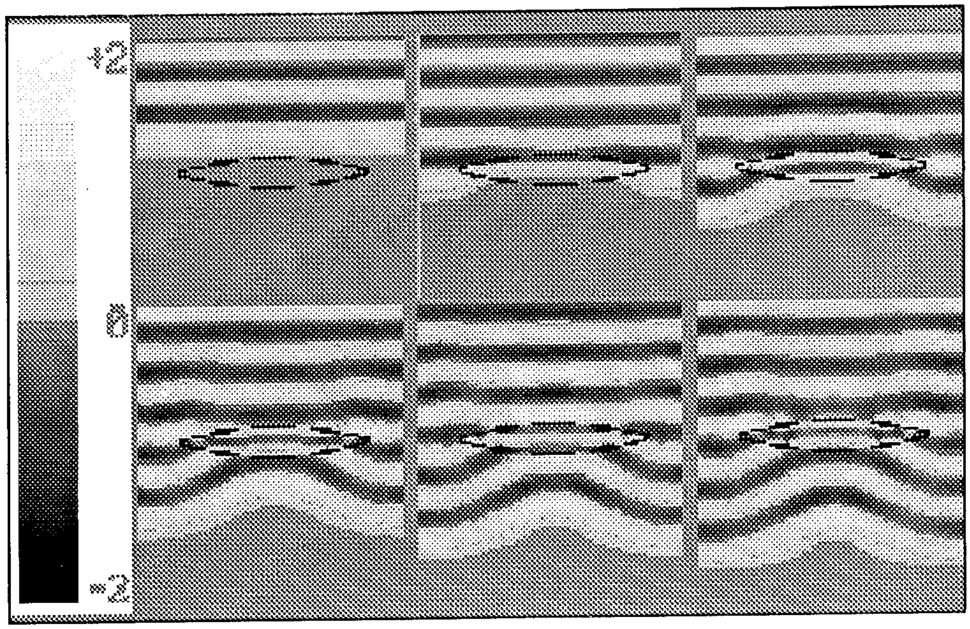
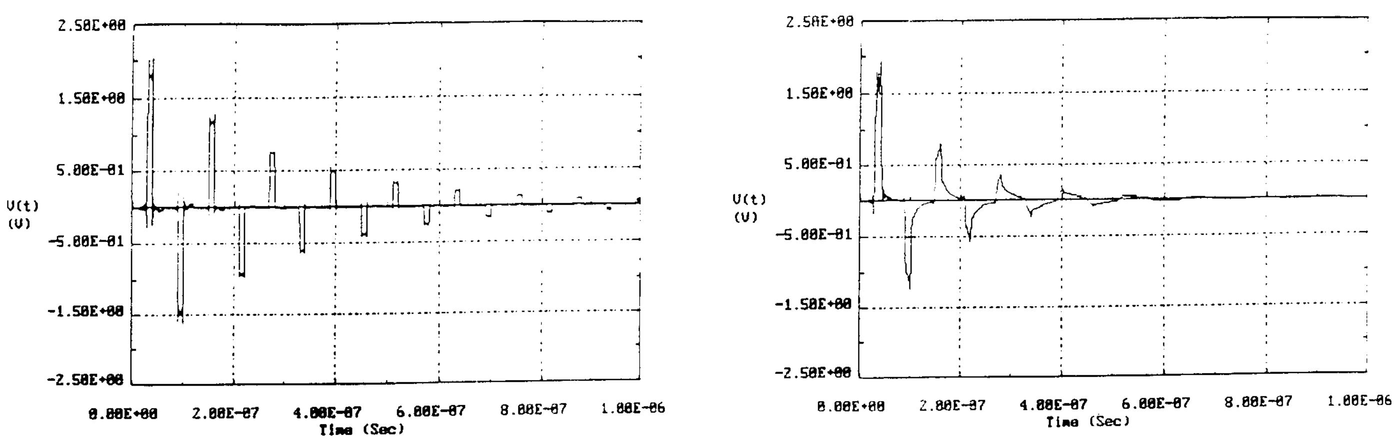


Fig. 1. A series of photographs that illustrates the focusing action of a dielectric lens ($\varepsilon_r = 4$) when excited by a sinusoidal plane wave. The series starts at the top left-hand corner, continue from left to right, and ends at the lower right-hand corner.



(a) (b)

Fig. 2. Illustration of the transient analysis capabilities of the Nuline software package. The total voltage is at an open-circuit load for both (a) perfectly conducting and (b) lossy ground return plane cases [14].

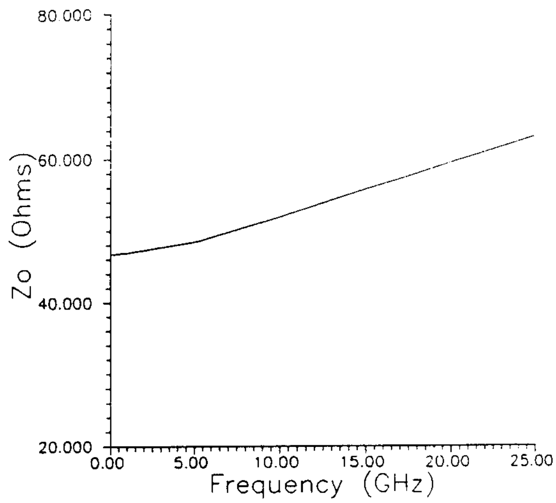


Fig. 3. Characteristic impedance of a microstripline as a function of frequency. Line width = 1 mm, dielectric thickness = 1 mm, box height = 10 mm, and dielectric constant = 10.

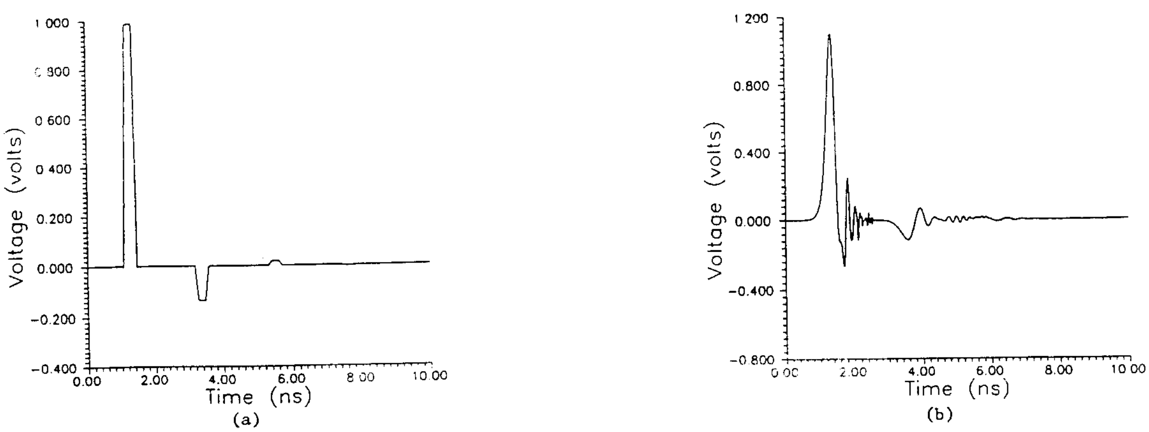


Fig. 4. Voltage at the output port of line T.Line of Fig. 3. The line is assumed to be terminated by a 50 Ω resistor in series with a diode. The default SPICE model is used for the diode. A 1 V voltage source in series with a 50 Ω resistor was placed at the input end of the T.Line. The line parameters at 1 GHz were used in these calculations. (a) Output voltage when dispersion is neglected. (b) Output voltage when dispersion is taken into account [15].

3. Electric- and magnetic-field vectors in cylindrical waveguides

This software package [16] calculates and plots the electric- and magnetic-field vectors associated with the various TE and TM modes in cylindrical waveguides. The program is based on analytical expressions for fields in waveguides of cross sections shown in Fig. 5. Figure 6 shows an example plot of the electric- and magnetic-field vectors. A newer version of this software that provides color display of the electric and magnetic field vectors in cavities will be published soon by CAEME.

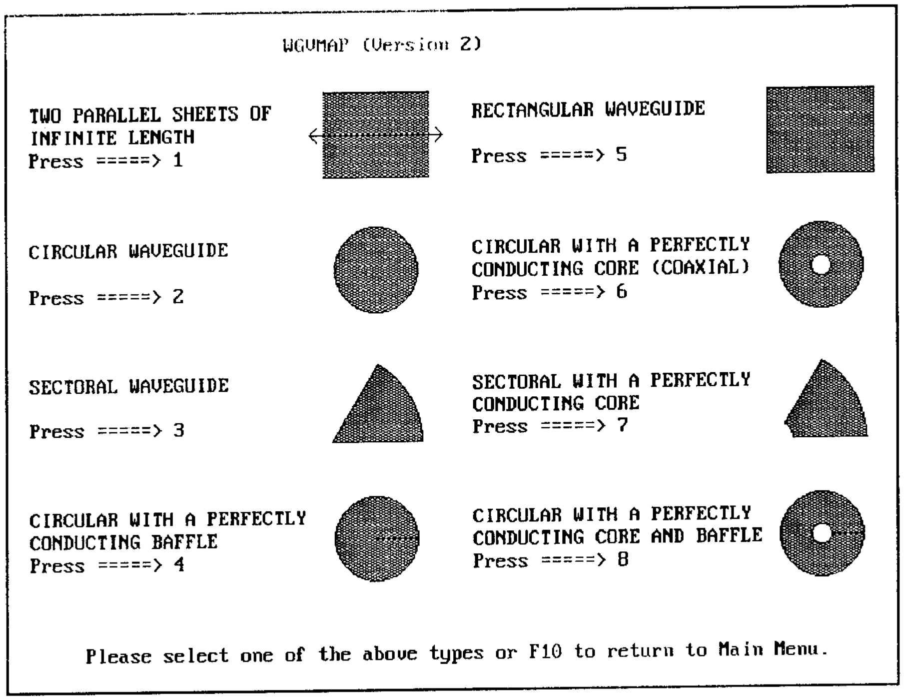
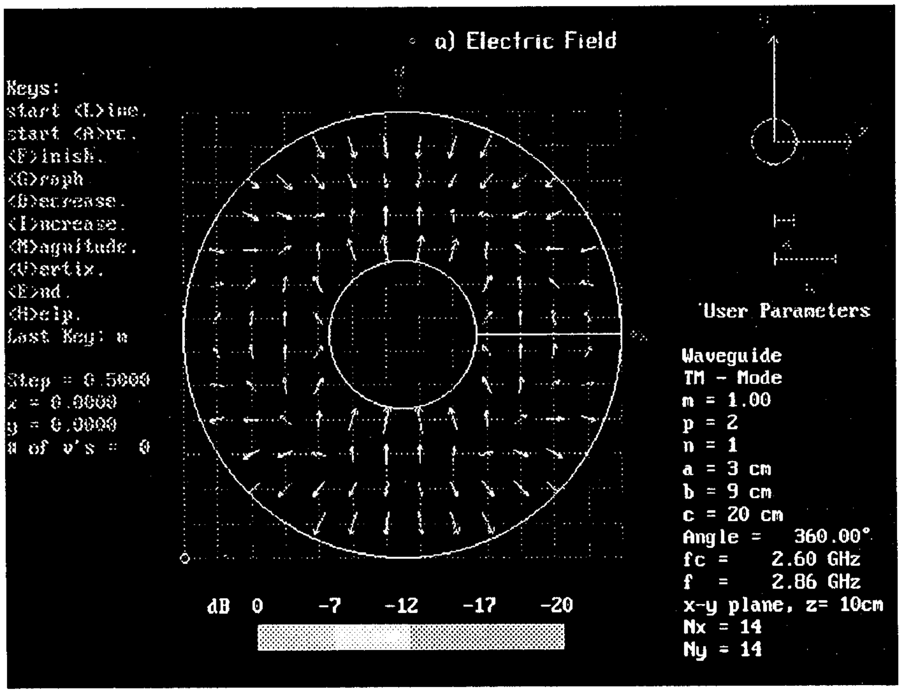


Fig. 5. Cross sections of cylindrical waveguides that may be analyzed using WGVMAP [16].

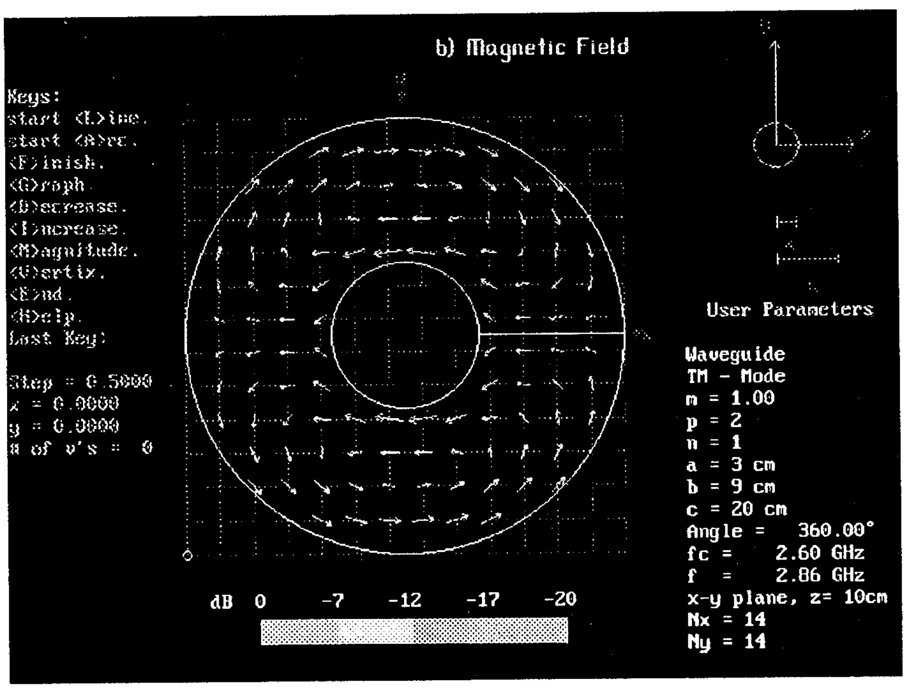
4. Numerical techniques in electromagnetics

This software package was developed by the group at the University of Utah and includes software suitable for an introductory course on numerical techniques in electromagnetics [17]. Both the finite-difference and the method of moments solution procedures are described. Examples of the finite-difference programs include calculation of characteristic impedance of strip and microstrip lines, the first TE and TM modes in ridged waveguides, and the junction capacitance of two coaxial cables. The first two examples are based on finite-difference solutions in cartesian coordinates, while the junction example is based on solution of Laplace's equation in the cylindrical coordinate system. Method of moments programs, on the other hand, include calculation of charge distribution on wires raised to specified voltages, the capacitance of a parallel-plate capacitor (including fringing effects), and the TM polarization, 2D scattering from an inhomogeneous dielectric cylinder of arbitrary cross section. Figure 7 shows the geometry of a parallel-plate capacitor for the method of moments calculations and the results of C/C_0 versus the spacing between the plates. C_0 is based on the geometry of the capacitor and neglects the fringing effects. Figure 7 demonstrates that neglecting the fringing capacitance may make values of C_0 in error by as much as 300 percent.

The above examples are just samples of the software available in the first CAEME book. Additional features are being discussed in other journal and magazine articles.

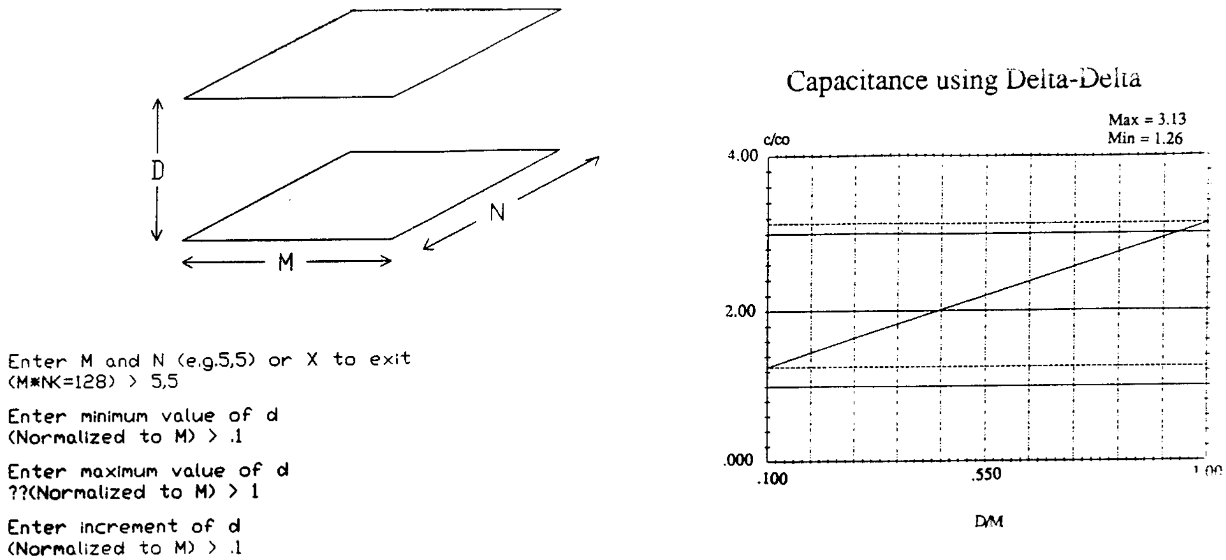


(a)



(b)

Fig. 6. An example of the WGVMAP resulting (a) electric and (b) magnetic fields associated with the TM_{11} (P = 2) in a circular waveguide with a perfectly conducting core and baffle. The radius of the center and outer conductors are 3 cm and 9 cm, respectively. The calculated cutoff frequency $f_c = 2.6$ GHz [16].



(a) (b)

Fig. 7. The parallel-plate capacitor example used to illustrate the method of moments solution procedure [17]. (a) Geometry of the parallel-plate capacitor. (b) The calculated capacitance C normalized with respect to $C_0 = \varepsilon_0 NM/D$ to illustrate the fringing capacitance $(C - C_0)$ effect.

IV. INTEGRATION OF SOFTWARE IN CURRICULUM AND CLASSROOM TEACHING

With the availability of a significant amount of software for EM education from CAEME and other commercial sources, it is important to assess the effectiveness of these new tools in classroom teaching and develop procedures that promote their effective use in education. Routine classroom teaching is significantly different from computer-based instruction, and concerted efforts must focus on developing new teaching techniques.

The CAEME Center addressed these new challenges by expanding its activities to include the following new tasks:

1. Develop educational tools to help the integration of software in classroom teaching. This includes new homework assignments, open-ended design problems, and simulation of EM-based practical applications such as xerography, optical fibers, doppler radar, etc. These applications may be used in stimulating students' interest in and out of classroom teaching.

2. Focus some of the workshop activities on discussing the issue of effective integration of computers and software tools in teaching.

   A workshop that addressed this issue has already been held in August 1992 in Salt Lake City, Utah. Throughout the presentations and discussion sessions, it was clear that educators agree that computer use in education is a necessity. It provides a unique opportunity to boost engineering education. As educators continue to use computers in their teaching, however, they discover

some limitations of this technology. Among the problems often cited is the congested curricula. A standard teaching procedure is based on text materials and laboratory instruction. With the introduction of computers, however, discussion of software and its uses and capabilities replaces some of the standard textbook and laboratory instructions. It is not clear how much of the standard instruction should be replaced by computer- and software-related instruction, and procedures to ensure the students' self study of the deleted portions of the standard instruction must be developed and enforced, and their effectiveness be carefully evaluated.

Furthermore, it is not clear if students would independently understand physical principles and mathematical procedures underlying the often-attractive graphical representation of simulation results. Tutorials describing the advantages and limitations of adopted solution procedures and quiz sessions must accompany routinely developed simulation software. Finally, the role of instructors in this era of computer-based instruction must be carefully defined. It is suggested that with the one-on-one tutoring capability of well-structured computer-based lessons, instructors may need to focus on difficult topics and leave routine ones to self study by students.

Many other timely topics were discussed during the Salt Lake City workshop, and a full proceedings will be published as a chapter in the *CAEME Software Book*, Vol. II.

3. Use of interactive video and multimedia lessons in EM theory and applications. An interactive video lesson includes access to multimedia information from video, software, and animated graphics, and access to multimedia instruction including tutorials and quizzes. Depending on a student's response, the interactive video application may direct the student to perform one of several available options. For example, a student who needs additional explanation may be directed to perform additional simulations, view additional segments of a video, or access a simpler version of the quiz with tutorial comments. At the end of the quiz session, the student's performance is evaluated and reported to the instructor.

   CAEME has already developed four interactive video lessons using the QUEST authoring software [18]. Main features of the developed lessons include

   - Access to and specific assignments from software packages in the *CAEME Software Book*, Vol. I.

   - Access to all or part of the experimental or computer-generated videos distributed by CAEME. Portions of these videos have been transferred to two laser discs (30 minutes each), and specific frames of the video sections are accessed by QUEST through a videodisc player (e.g., Sony LDP 1450).

   - Animated graphics of various dynamic phenomena associated with the topic of the lesson. QUEST [5, 19], as well as other authoring systems, provides relatively easy-to-use capabilities for creating animated graphics so valuable to the effective explanation of the dynamic electromagnetic fields. Examples of some of the developed animated graphics will be discussed in the following section.

- Quiz sessions that help evaluate the students' understanding of key topics in the lesson, guide students through correct solution procedures, and suggest specific avenues (additional reading, software simulation, or video review) to help students in their understanding. In all cases, the multimedia lessons were structured such that results from the quiz sessions are reported to the instructor.

In the following section, features of the four developed EM multimedia lessons will be described.

V. EXAMPLES OF MULTIMEDIA LESSONS IN ELECTROMAGNETICS

In all the four multimedia lessons developed by CAEME thus far, the animation, access to video, simulation, and quiz features described above were implemented. In each of the following examples, however, we will attempt to highlight one of these features.

A. Example 1: Electromagnetic Waves

The objective of this lesson is to introduce the student to basic propagation characteristics of traveling and standing waves. The main menu of the lesson is shown in Fig. 8, where it may be seen that the lesson provides access to video demonstrations on

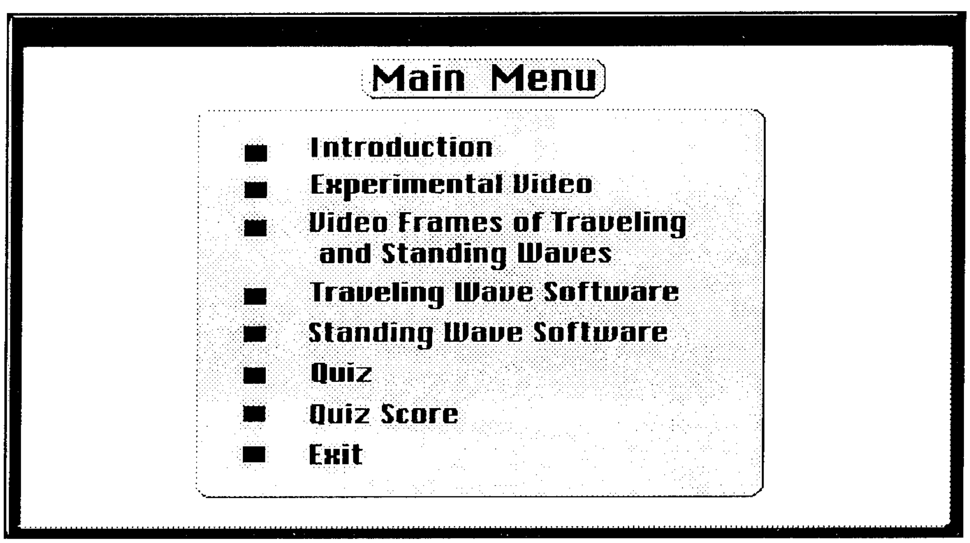


Fig. 8. Main menu of the multimedia lesson on electromagnetic waves. The lesson includes access to experimental video, two CAEME software packages [20, 21], animated graphics, and a quiz that consists of five questions.

standing waves [11] and to two software packages from the CAEME book [20, 21]. It includes animated graphics and tutorials on some basic properties of traveling and standing waves and a quiz session.

We will use this example to demonstrate the animated graphics and access to video features of a multimedia lesson.

Video Frames of Traveling and Standing Waves

When this option is selected from the main menu, the screen shown in Fig. 9 is displayed. This screen gives the student the option of selecting and focusing on the topic of either traveling or standing waves. Let us briefly consider the content of each topic.

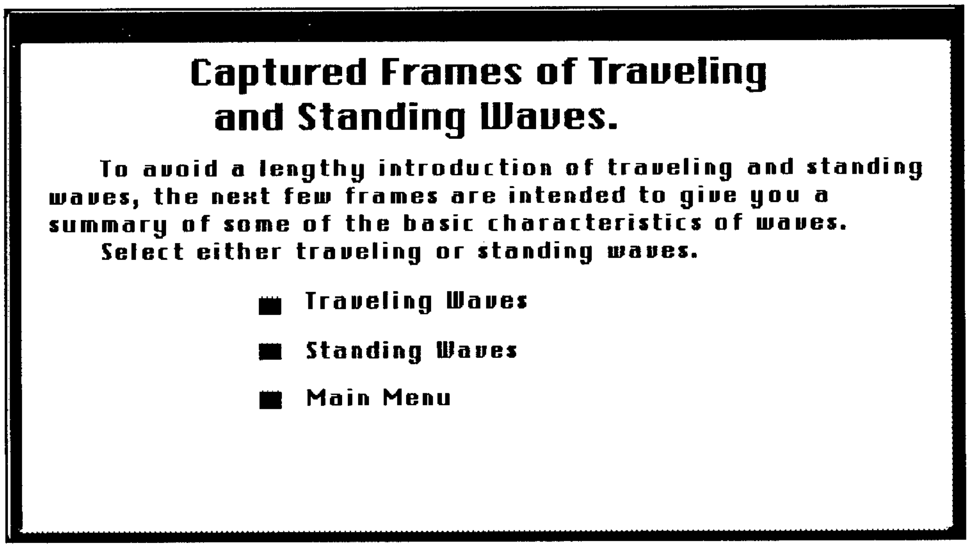


Fig. 9. A menu that provides access to the traveling and standing waves topics.

Traveling waves: In this section, the student is introduced to the basic propagation properties of a traveling wave and the relationship between the associated electric and magnetic fields. An example screen in this option is shown in Fig. 10, where the electric and magnetic fields associated with a plane wave propagating in air are demonstrated dynamically using a sequence of animated graphics. This dynamic and animated presentation of the propagation characteristics of waves makes the use of computers far superior to routine textbook static-type teaching. At the end of the traveling wave section of the lesson, it is suggested that the student access and perform independent simulations of some specified aspects of wave propagation using the CAEME software [20, 21].

Standing waves: Upon selecting the standing-wave option in the menu of Fig. 9, the new menu of Fig. 11 is displayed. This menu is quite comprehensive. It allows the student to access a short section of video that experimentally demonstrates mechanical standing waves, a brief tutorial with animation on characteristics of standing waves, and additional captured small sections of the video on experimental demonstrations of standing electromagnetic waves. The video sections on mechanical waves and the electromagnetic waves are included in the video available with the CAEME book [11].

When the "Electromagnetic Standing Waves" option from the menu of Fig. 9 is selected, the student will be briefly introduced to a tutorial on the cause and propagation properties of standing waves. An animation that demonstrates the interference between two waves of equal magnitude, of the same frequency, and propagating in opposite directions is included in this section (see Fig. 12). The basic properties of a standing

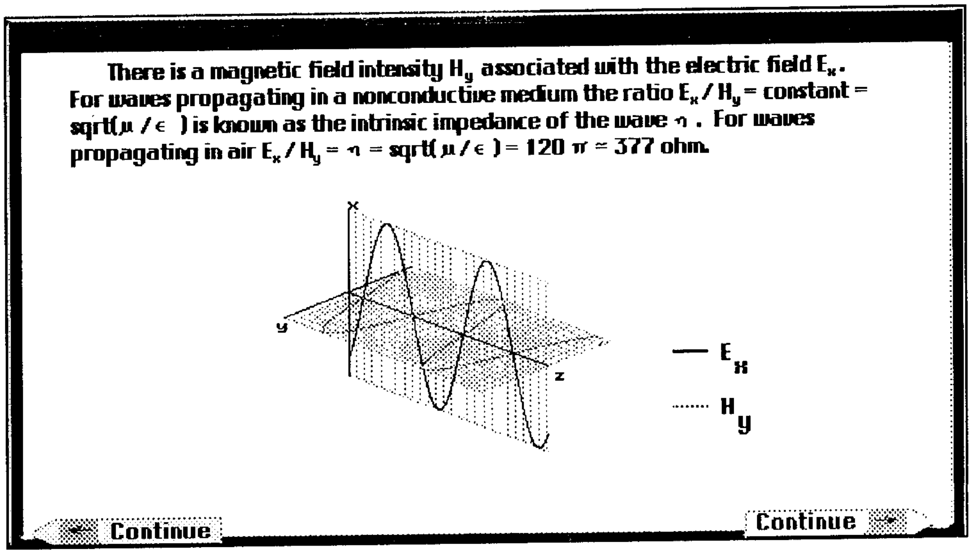


Fig. 10. An example that demonstrates the animated graphics capabilities of the "electromagnetic wave" multimedia lesson. The figure shows in phase sinusoidal electric and magnetic fields. These fields are perpendicular to each other and to the direction of propagation (z).

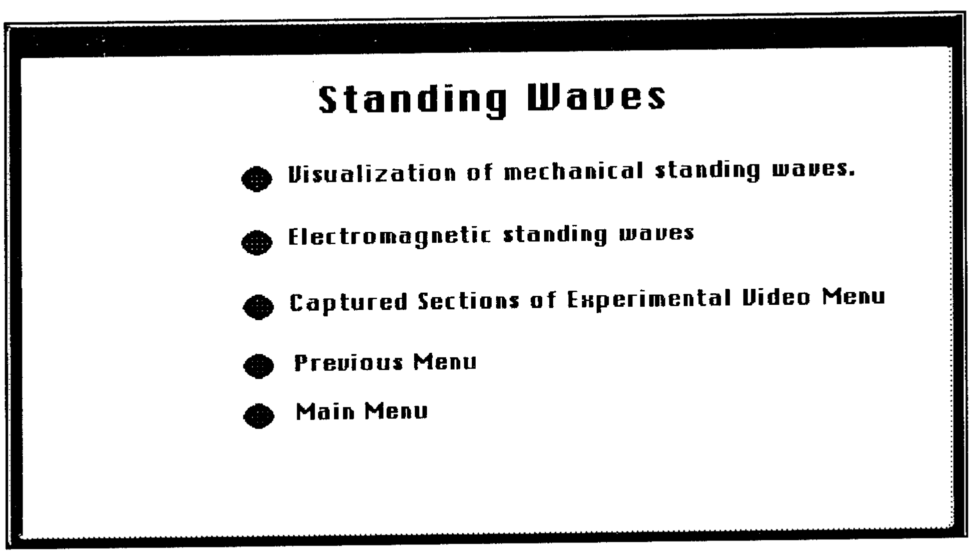


Fig. 11. The standing waves menu. It includes a comprehensive review and demonstrations of some fundamental characteristics of standing waves. In addition to various segments of videos and animated graphics, it accesses tutorial information and instructions.

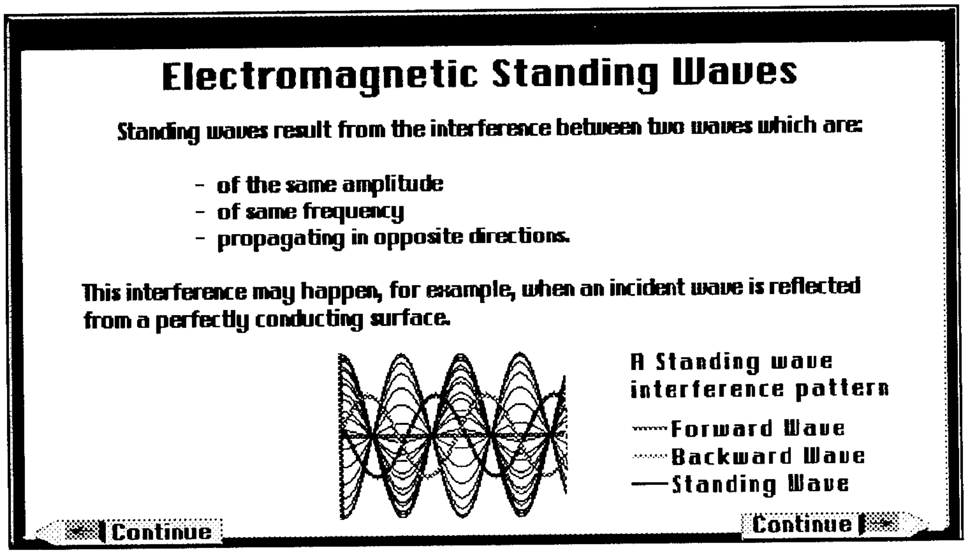


Fig. 12. Dynamic illustration of the concept of standing waves. Two sinusoidal plane waves of the same frequency and propagating in opposite directions (green and purple curves) interfere to produce the resulting standing wave (white curve).

wave are also summarized. Aspects such as distances between successive nulls in electric and magnetic fields and locations of nulls from short- and open-circuit terminations of TEM lines are discussed. Once again, the animated graphics illustrating the interference between two waves and the visualization of the characteristics of the resulting standing wave provide excellent demonstrations of the advantages of using computers to teach dynamic electromagnetic fields.

B. Example 2: Electrostatic Charges and Coulomb's Law

The purpose of this lesson is to review basic concepts concerning interactions between charged particles. To accomplish this, the student views a video presentation on the measurement of charge and an experimental verification of Coulomb's law. The main menu of the lesson that appears after the student signs his/her name is shown in Fig. 13. This lesson provides access to a section of the video on experimental demonstrations for teaching electromagnetic fields and energy [11], to CAEME simulation software relevant to the lesson's topic [12, 21, 22], and also to tutorials on electrostatic charges, their forces, and techniques for their measurement.

Besides the access to sections of the video on Coulomb's law and measurement of electrostatic charges, the lesson provides an attractive computer-based quiz session. This includes animated graphic features wherever appropriate and also interactive remediation for helping and guiding the student in solving the quiz problems. For example, in quiz problem number 3, the student is asked to determine the angle between an electrostatic charge Q and an infinitely large plane charged with a charge density ρ_s. If the student clicks on the wrong answer, the program will first advise the student that his/her answer

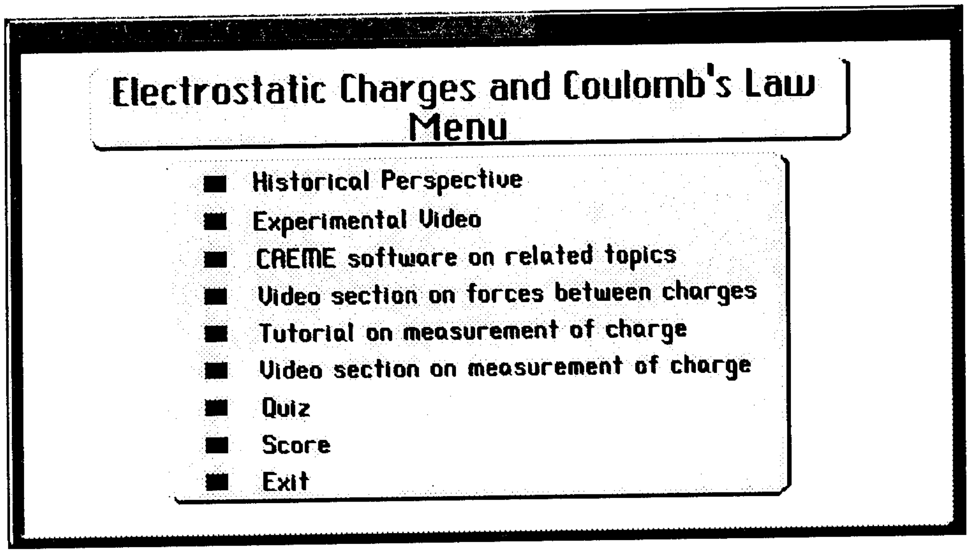


Fig. 13. Main menu of the multimedia lesson on electrostatic charges and Coulomb's law.

is incorrect (see Fig. 14) and then will proceed to provide guidance through one aspect of the required analysis. For example, in this case, the student will be asked to calculate the electric field associated with the infinitely large plane charged with a charge density ρ_s.

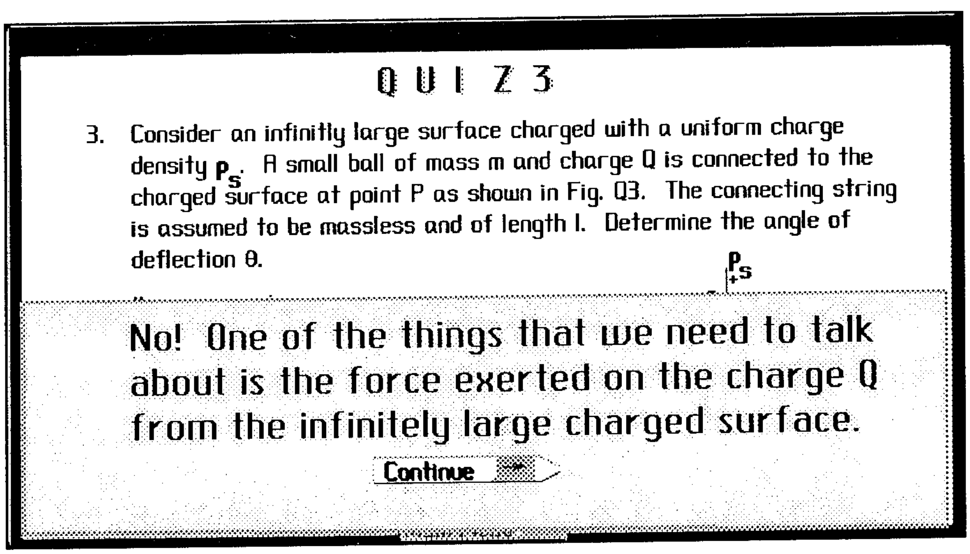


Fig. 14. An example of the response a student receives when a wrong answer is selected. Multimedia lessons are structured so as to provide remediation for helping and guiding the students when solving the quiz problems.

It will be pointed out that he/she needs to apply Gauss' law for the electric field, and to do this a Gaussian surface that takes advantage of the symmetry consideration and the resulting direction of the electric field needs to be established [23]. The student's selection of the appropriate direction of the electric field resulting from an infinitely large

charged plane is indicated by clicking on the appropriate option as shown in Fig. 15. If a wrong selection is made, the student will be guided so as to recognize aspects of the symmetry consideration, and he/she will even be led to the selection of an appropriate Gaussian surface as shown in Fig. 16. Upon the selection of the suitable Gaussian sur-

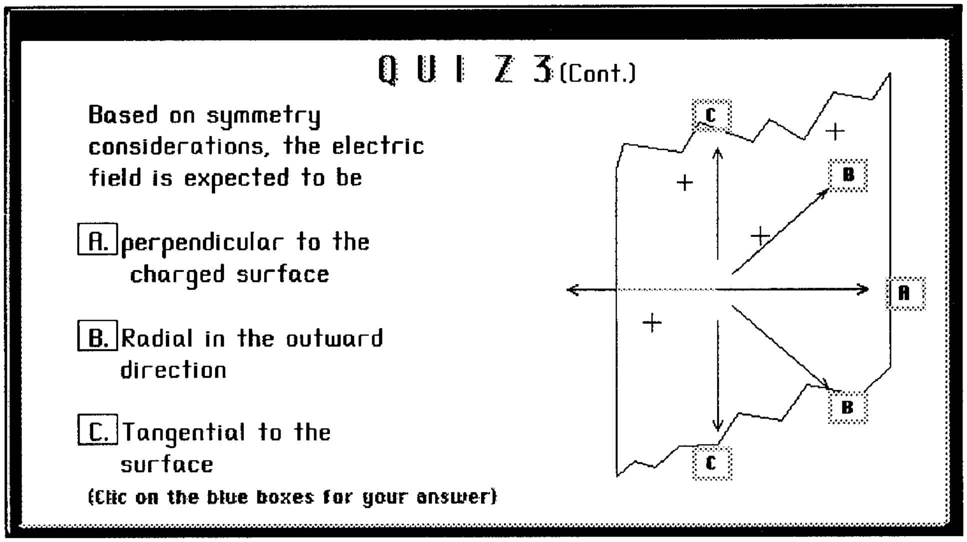


Fig. 15. A display of a multiple-choice question intended to help students identify the correct direction of the electric field associated with an infinitely large charged plane.

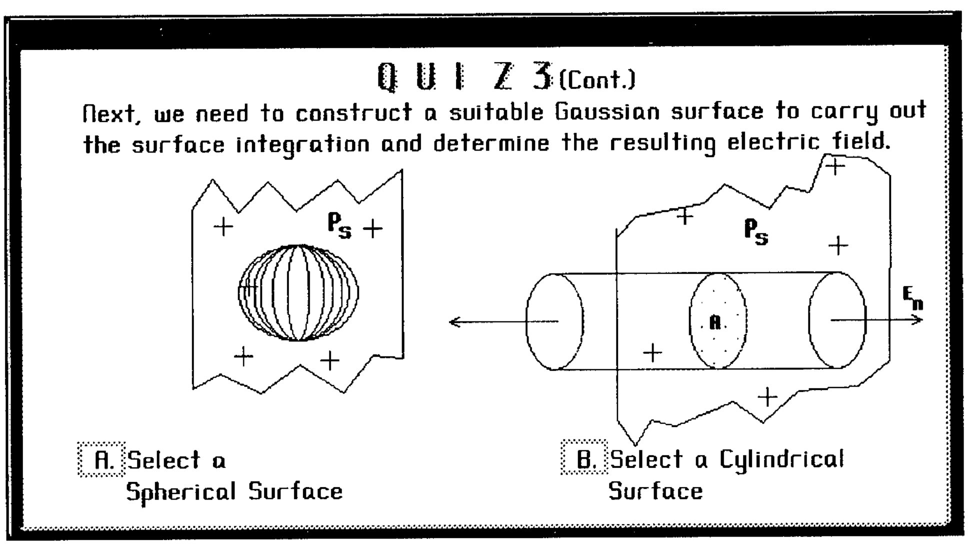


Fig. 16. A schematic demonstrating (a) an incorrect and (b) a correct option of selecting a Gaussian surface for evaluating the electric field associated with an infinitely large plane charged with a charge density ρ_s. If a wrong answer is selected, the student is advised to select option B to take advantage of simplifications when integrating the electric field E_n over the closed surface.

surface and the correct calculation of the electric field from an infinitely large charged surface, the student will be asked to attempt a second answer to the quiz. If the answer is still incorrect, the student will receive a second level of remediation with the additional analysis needed to answer this question. In particular, the analysis concerning balancing the electric and gravitational forces on the suspending string with the substitution of the correct value of the electric field, as described in the earlier portion of the analysis, should be fairly simple for the student to identify the correct answer to the quiz.

It should be emphasized that through this example, we attempted to demonstrate the integration of the visualization, animation, and interactive features of the multimedia lesson. The inclusion of sections of video help visualize experimental aspects of measuring charges, while access to CAEME software and interactive guidance of the student through the quiz session clearly distinguish multimedia lessons from classical static or textbook-type teaching.

C. Example 3: Dielectric and Conducting Materials

The objective of this lesson is to review the conducting and dielectric properties of materials, describe various polarization mechanisms, and quantify the conduction and polarization currents as well as the polarization charge that results from the interaction of materials with an externally applied electric field. The main menu of the developed lesson is shown in Fig. 17, where it may be seen that traditional features such as access to video segments, CAEME software, and a quiz session are included.

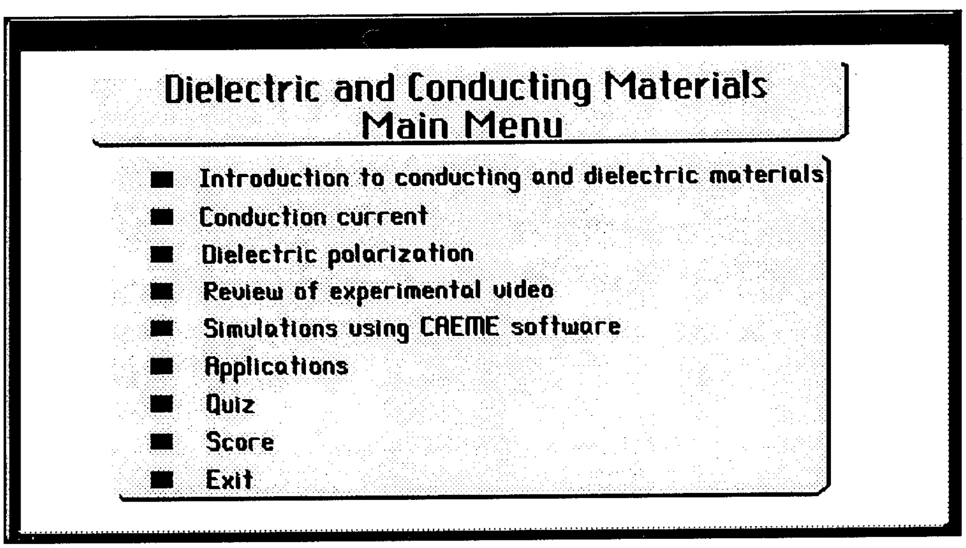


Fig. 17. Main menu of the multimedia lesson on dielectric and conducting materials.

This lesson, however, has additional attractive features. This includes interactive animations and specific software assignments to help lead students to understand some fundamental concepts of the lesson, and also a hypertext type of tutorials whereby key words are highlighted and additional explanations are made available to students upon request.

Regarding the interactive animation feature, let us consider the explanation of the various polarization mechanisms. In the lesson, it is initially stated that there are three main polarization mechanisms in pure substances, and a menu is provided to access an explanation of each of these mechanisms. Upon access of the electronic polarization option, for example, the student is shown a classical atomic model of a positively charged nucleus surrounded by a cloud of orbiting electrons. The student is then asked to apply an external electric field by clicking the mouse and watch the shifts in the centers of the positive and negative charges in opposite directions, thus creating the electric dipole. In the orientational polarization case, a color graph of a section of material is shown and the permanent electric dipoles are displayed in random motion under the influence of their thermal energy. When the student applies an external E-field, he/she watches, in real time, the alignment of these dipoles in the direction of the E-field and, although still in motion, they maintain their alignment along the field. Figure 18 shows stills that illustrate this process.

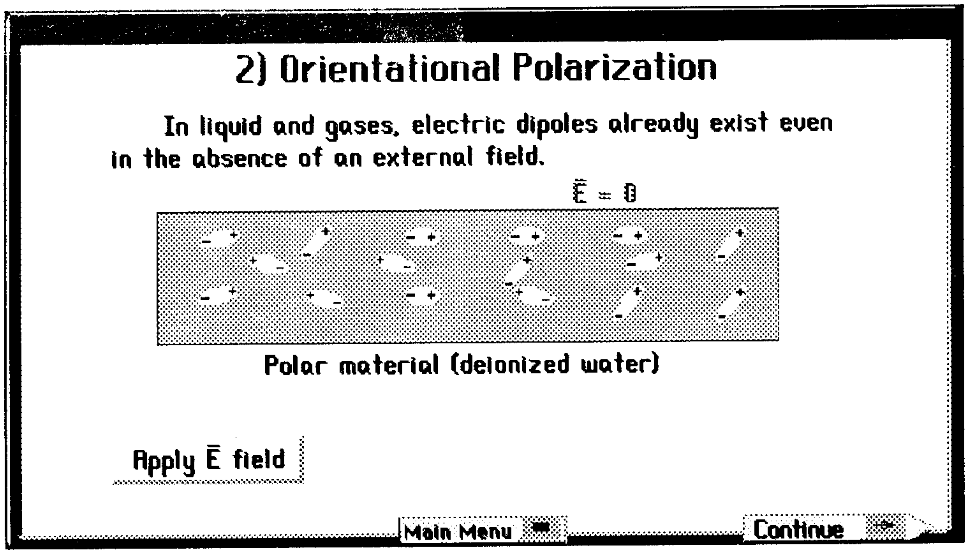
Based on these types of animated graphics which provide an avenue for the student to interact with the process by applying the E-field or changing the type of material, concepts such as polarization and induced polarization currents and charges may conveniently be introduced. Their presence is further appreciated by students.

The other new feature of this lesson is providing students with specific assignments to use CAEME software. Figure 19a shows a simulation example that will help students understand the reduction of the electric-field strength inside a dielectric material as a result of the material's polarization. The first part of the assignment provides access to the ROSEM software [24] and shows the student the expected result from his/her simulation effort "screen display." Upon continuing, a second screen with the remaining part of the assignment is shown. Once again, access to the software and to a display of the expected results is provided as shown in Fig. 19b. After performing the simulation, the student is asked to explain the results in an interactive fashion as shown in Fig. 20. Depending on the answer, the student may either be asked to carefully compare the results as shown in Fig. 21 or be guided through a detailed, often graphical explanation of the expected answer.

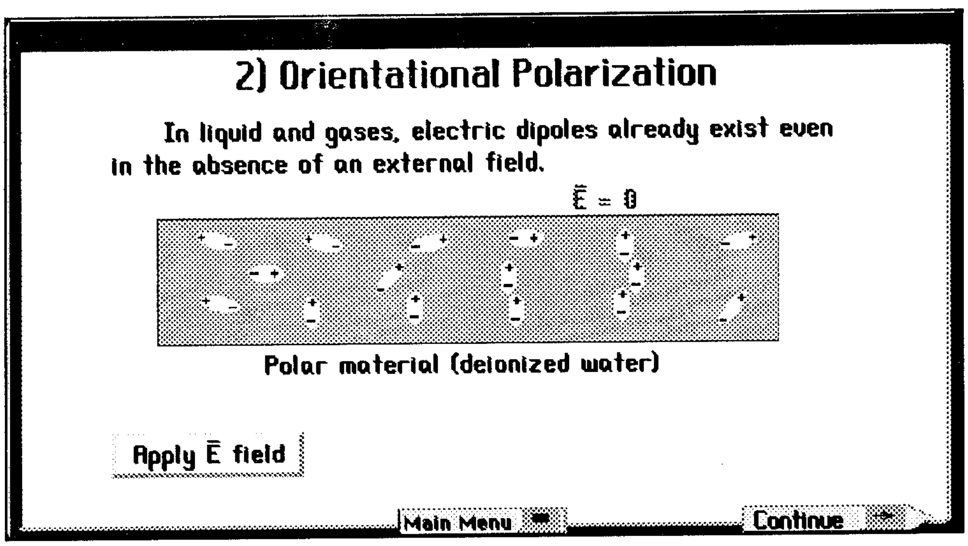
The above discussion provides an example of a specific simulation assignment procedure that may help guide students through an understanding of a physical phenomenon. Other examples are available in this as well as other multimedia lessons developed by CAEME.

D. Example 4: Tic-Tac-Toe Review Test in Electromagnetics

The purpose of this multimedia application is to provide a review test of several basic concepts routinely covered in an introductory course in electromagnetics. As the student accesses the application and enters his/her name, the overall Tic-Tac-Toe board shown in Fig. 22 appears on the screen. The various question categories include elements of an introductory course in electromagnetics. Topics such as vector algebra, fields, Maxwell's equations, EM waves, and dielectric polarization are routinely covered in these courses. It may also be noted that the question board includes a video category in which the student is shown a short section of a video and then asked to answer a question. In addition to the fun nature of this lesson, many of the questions include animation; this emphasizes an additional advantage of having this Tic-Tac-Toe game played on a computer. The arrangement of the categories is randomized after each questions to avoid a fixed arrangement of the topics.

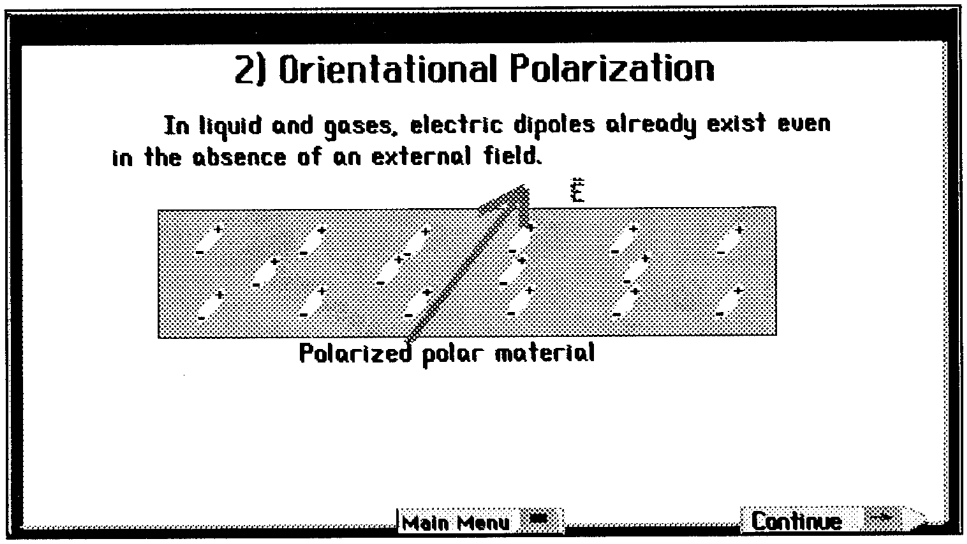


(a)



(b)

Fig. 18. A series of stills that illustrates the concept of orientational polarization. (a) and (b) show the random orientation of permanent electric dipoles and their continuous motion in the absence of an external electric field. (c) Alignment of the permanent electric dipoles in the direction of the external electric field.



(c)

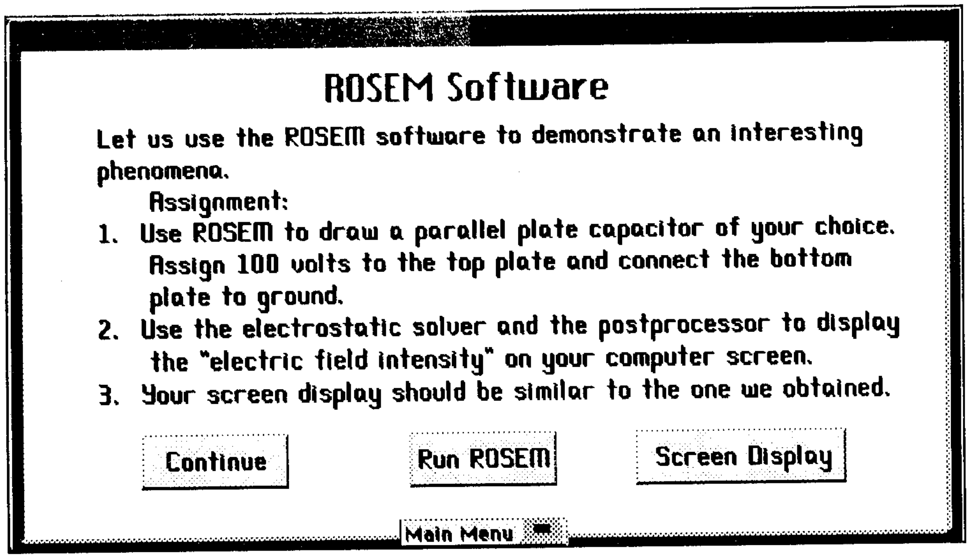
Fig. 18 (cont.)

In designing this review test, each question category was divided into subcategories, each of which includes several questions. For example, the category on Maxwell's equations includes subcategories on general aspects of these equations, Ampere's law, Gauss' law, and Faraday's law. Also, the category on vector operations includes subcategories on vector algebra, integral operations, and differential operations. An example of the questions in the vector differential operation subcategory is shown in Fig. 23, in which the student is asked to identify the relationship between the differential vector operations and the flux representations of some vector fields. It is difficult to demonstrate in this paper some of the dynamic, animation, and interactive aspects of these questions, but it suffices to indicate that students find this lesson fun, exciting, and most important, instructionally useful and certainly helpful in solidifying their understanding.

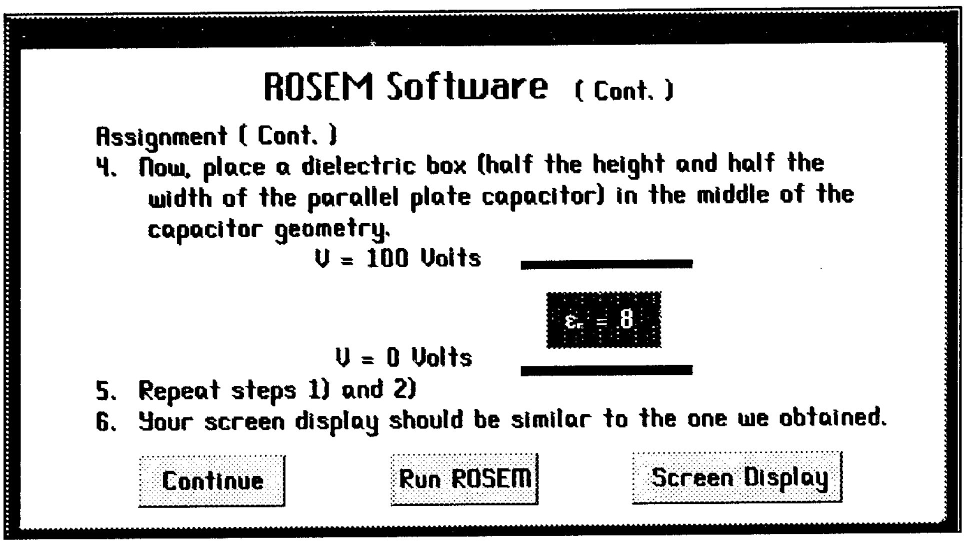
VI. DISCUSSION AND CONCLUSIONS

The grant from the National Science Foundation for establishing CAEME provided the electromagnetic community with a unique opportunity to align EM and microwave education with the nineties. Software packages that provide broad coverage of all topics in an introductory course in electromagnetics were developed, and efforts are underway to develop additional software for volumes II and III of the CAEME books and to further explore avenues to promote integration of computers and software tools in classroom teaching. Besides the software developments, the mere existence of the CAEME Center and its widespread activities increased awareness of problems facing electromagnetic education, helped faculty share possible solutions, and provided avenues to effectively disseminate available software and other related information.

In addition to illustrating some of the features of the developed software, examples of multimedia lessons developed to help integrate CAEME software in teaching were described. It is shown that authoring software such as QUEST is available, and opportunities to develop lessons that combine multimedia information from video, software, and animated graphics with multimedia instruction, including tutorials and



(a)



(b)

Fig. 19. An example of software assignment that helps guide students through simulation using CAEME software (e.g., ROSEM [24]). (a) Simulation example of an electric field in a parallel-plate capacitor. (b) Simulation of the electric-field intensity in part (a) when a dielectric slab is inserted between the plates.

quizzes, are not only feasible but also affordable. Software and hardware requirements for developing such lessons may be purchased at an estimated cost of less than $3,000 (excluding the 386 computer). CAEME is an industrial affiliate of Allen Communication, and copies of QUEST may be obtained through CAEME at a 20% discount from the much-reduced educational price. Based on instructor and student comments on these lessons, it is generally believed that multimedia applications will play a significant role in the future integration of computers and software tools in classroom

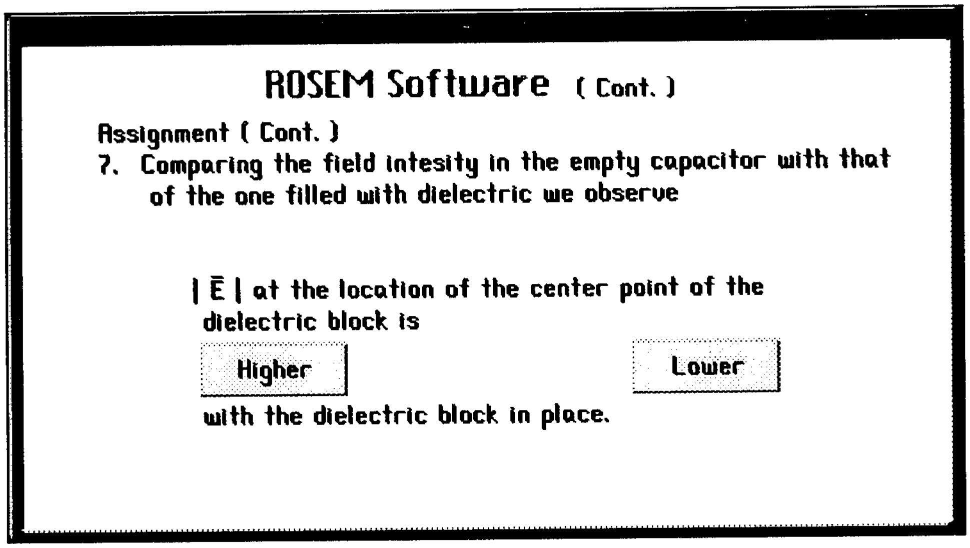


Fig. 20. A quiz prepared to evaluate students' understanding of the simulation results. The electric field inside the dielectric is expected to be lower than its value before inserting the dielectric slab. The student is asked to make a selection between the two choices.

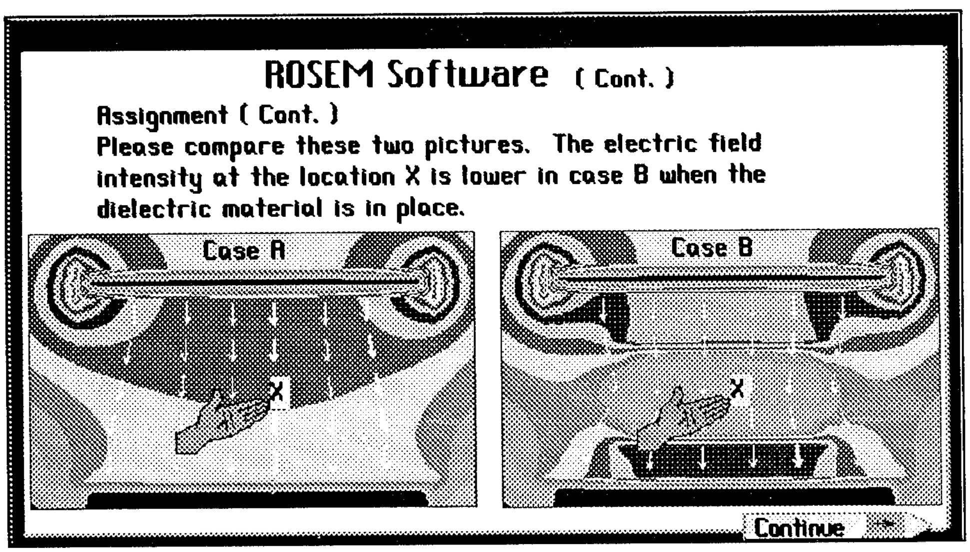


Fig. 21. Electric-field intensity in the region between the plates of a parallel-plate capacitor. Case A is for the air-filled capacitor, while case B is for the case when the dielectric slab of $\varepsilon_r = 8$ is inserted in a central subregion between the plates.

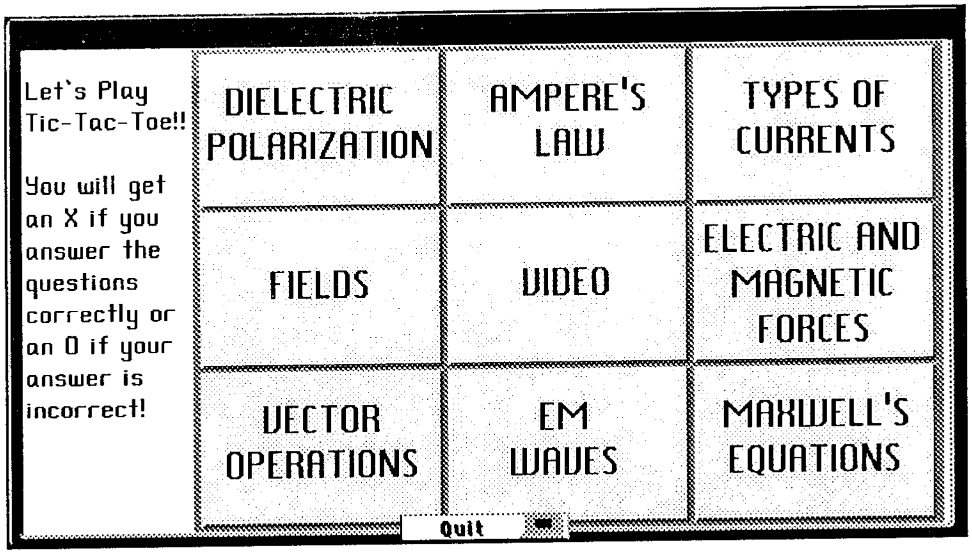


Fig. 22. Main menu of the Tic-Tac-Toe interactive video lesson. This is a review lesson on some basic concepts in introductory electromagnetics.

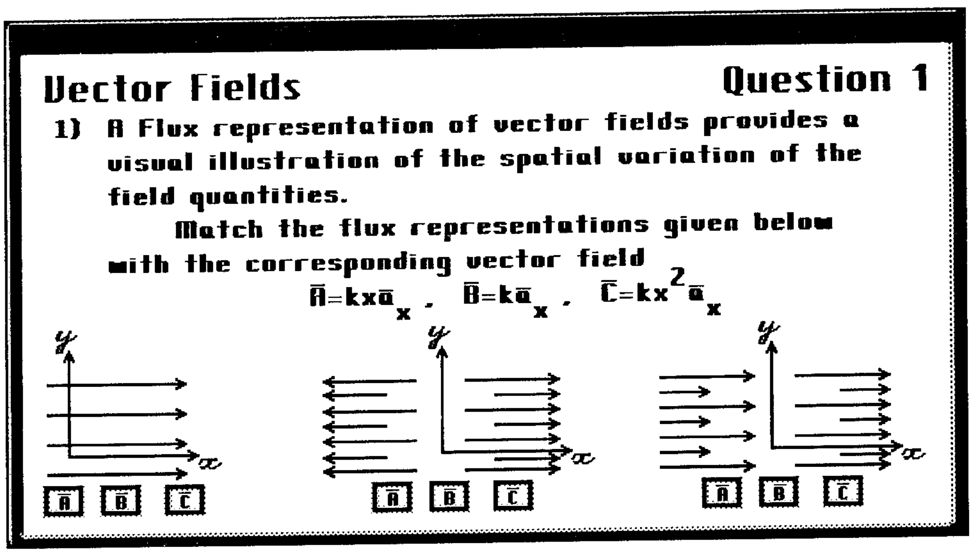


Fig. 23. An illustration of the type of questions included in the Tic-Tac-Toe review lesson. Flux representations of vector fields are sketched and the student is asked to match the flux representation with the appropriate expression of the vector field.

teaching. Future developments in the CD-ROM and digitized-video technologies will significantly help in the distribution of these highly interactive and visual lessons.

As CAEME continues to proceed with its activities, faculty and institutions are encouraged to join in and seize this opportunity to help boost EM education. With the publication of the new journal, *Computer Applications in Engineering Education*, faculty now have an exciting opportunity to publish their work in an attractive peer-reviewed, multidisciplinary journal. CAEME will also continue to organize special sessions and

workshops to help faculty present new developments, exchange ideas, express concerns, and share successes. CAEME will also continue to provide seed funds so that its faculty can continue their work on new software development projects. To this end, corporate support and participation by professional EM societies is crucial. Based on the present level of support, CAEME's future is bright.

ACKNOWLEDGMENTS

The CAEME Center, its activities, and the software in the first book have all resulted from remarkable collaboration between participating faculty and outstanding commitment by their institutions. Some of the software packages were prepared by faculty who received CAEME grants, while others were contributed by faculty and institutions interested in and supportive of the CAEME effort. To all CAEME faculty members whose names appear in the CAEME book, congratulations on a successful effort, and I am indebted to you for your outstanding contribution.

I am also grateful to members of the policy board for their vision of the CAEME mission and for their remarkable efforts that made the Center a success. Members of the board who helped establish CAEME include Irene C. Peden, David Chang, Zvonko Fazarinc, Robert E. Collin, Gary Wojcik, Warren Stutzman, Barry Perlman, Clayton Paul, Rudy Stampfl, Hal Kimrey, Philip Green, and Vaughn Cable.

I am also indebted to colleagues from John Wiley & Sons, Inc. who supported the publication of the new journal, *Computer Applications in Engineering Education.* Now that engineering faculty can publish and be recognized for this work in this area, the future of a "computer-based engineering curriculum" is certainly bright.

I would like to thank our corporate sponsors -- Hewlett-Packard, Motorola, Lockheed, Texas Instruments, and Andrew Corporation -- for their kind support. Equally appreciated is the remarkable support the Center receives from the Electrical Engineering Department at the University of Utah and the CAEME staff. In particular, I am grateful to Holly Cox, Doris Marx, Octavio Andrade, Joe Breen III, and Paul Cherry, who generously supported CAEME development every step of the way. The professional commitment and outstanding work by Tom Reed is wholeheartedly appreciated. The CAEME Center was created as a result of Grant no. USE-8953523 from the Undergraduate Science, Engineering, and Mathematics Division of the NSF.

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MULTIMEDIA SELF-TRAINING PACKAGE FOR BASIC MICROWAVES LEARNING

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ABSTRACT

The purpose of this article is to present an original pedagogical product for teaching microwaves. It contains 9 lessons and is composed of 2 media :
- a handbook
- interactive educational software
It is a multimedia self-training product recommended for technicians and engineers working in conventional electronics and wishing to acquire advanced knowledge in microwaves in connection with their working structure. It can also be used in self access at the university by undergraduate students. In this last case, the authors will state in the conclusion, their observations following an experiment in computer aided learning (C.A.L.) carried out at the university of Lille.

WHY SUCH A PACKAGE ?

From the experience of microwave teachers [1] it has been noted that students of different classes always encountered the same problems such as :
* associating a mental image with abstract concepts
* giving a physical meaning to a mathematical expression
* understanding dynamic phenomena from static representation
* understanding rapidly the contents of the courses due to lack of specific vocabulary on the subject.

The package was made possible thanks to a French national project on the following subject: "Multimedia self-training in fields of high technological content and contributing to the expansion of firms".
The authors then saw the use of the computer through its interactive environment and the use of animated images, as a valid means of eliminating particularly important obstacles in the teaching of the basics of microwaves.

DESCRIPTION OF THE PACKAGE

The package contains 9 lessons that can be divided into 3 topics :
- a review of electromagnetics

- plane wave in free space ; plane wave in a metallic bounded medium ; theory of transmission lines
- The Smith chart and its practical application.

This self-training package is composed of a handbook and a piece of educational software.

1) The handbook

The authors think that the hanbook is essential. It contains all the theoretical information that would be boring on the screen. The advantage of the handbook is that it can be read without the help of the computer. However, a link exists between the two media of the package thanks to an acronym "computer" showing the learner how to refer to the software if necessary. Every lesson is set out in a conventional manner. Yet, whenever it is necessary to draw the learner's attention to an important concept or key sentence, this is done by means of small boxes on the right hand side of the page. Thus, the student can immediately grasp the essential points.

2) The educational software

The originality of the software lies in a different, yet complementary and pragmatic approach to the handbook by means of simulation, animation and interactive exercises where students' answers are carried out with a high degree of accuracy.
Access to the software is very ergonomic. Forward and backward screening allows the student to go to any screen page in the educational software, as and when required.
The software is self-contained in order to avoid continual reference to the handbook. However, a link does exist with the hanbook thanks to a special book-sign which appears on the right side of every screen page. When this function is "on", the page of the handbook concerning the subject being studied appears.

The computer equipment needed for operating this software is an AT personal computer with a hard disk, an EGA videocard and a mouse.

USE OF THE COMPUTER FOR BETTER UNDERSTANDING OF BASIC MICROWAVES

In the following paragraph by means of a chronological summary of the introductory course to microwaves, the authors will highlight some key points for which the computer can provide a greater level of understanding and a consolidation of knowledge acquired.

1) Review of Electromagnetism [2]

As soon as the student begins to study electromagnetics, he has difficulty understanding the physical meaning of basic concepts such as field vectors, the line integral or flux of a vector. It becomes essential to put animation and simulation at his disposal allowing him to "experiment" with these ideas and to form a mental image more easily.

For example, one only has to trace all the field vectors from a source, at all points of a path, to introduce the necessity of a line integral in order to calculate, for example, the common potential function in the electrostatic case.
The study of flux and divergence is undertaken very slowly. First, the use of an animated corkscrew on the screen allows one to orientate successfully on a surface. Then, a number of interactive exercises related to the study of simple field vectors are treated in a numerical way, without any mathematical formalism. It is only after this very concrete approach that the case of more complicated field vectors is tackled. After these exercises the understanding of Gauss's theorem and Ampere's theorem is immediate, since all the underlying elementary concepts are well established and understood [3].

2) Plane wave in free space [4]

a) Dynamic phenomenon

After the electrostatic and magnetostatic fields, time-varying phenomena are tackled, this leads naturally to wave propagation. Only very few students succeed in making a mental image of the double periodicity of the wave, in time and in space. This periodicity is easily demonstrated on a computer screen using animation, where at a given abcissa, a window shows the temporal variation of the field during the propagation of a linearly polarized wave.

b) Abstract concept of wave polarization

The circular or elliptic polarization of waves is often not well understood by the students. This may be shown by the displacement of two linearly polarized plane waves which are normal. It is then easy to observe the tip of the resultant field vector, describing a circle or an ellipse in a plane perpendicular to the propagation axis.

3) Plane wave in a metallic bounded medium [5]

The case of plane wave propagating in metallic bounded medium is introduced. The purpose is to progressively lead the learner to detect, without calculation, the possibility for a T.E.M. wave to propagate or not in a closed structure ; this is deduced from concrete criteria stemming from the Laplace equation. This part of the course calls for the use of specific vocabulary used commonly by those working in the field of microwaves. Ideas such as "transverse cross section of a guide", "open" or "closed" guide, "homogenous" or "inhomogenous" guide, "disjointed" conductors and so on, are encountered through a series of short interactive exercises. So, with this knowledge, the student can practice, on final tests which consist of interactive exercises, taking into account a lot of structures of propagation that one can find in microwaves [6] ; an example is given figure 1.

4) Transmission line [7][8]

a) An introduction to the distributed elements circuits

The public we are aiming our package at, has a certain degree of knowledge of low frequency electronics. It is therefore of interest to demonstrate how to go from low

frequency conventional electric circuit with discrete elements for which the dimensions of the circuits do not play any role, to the distributed elements circuits modeling the propagation of a high frequency T.E.M. wave. To this purpose, we have designed three animations at different frequencies, (figure 2). The first one shows a T.E.M. transmission line, 30 meters long, on which a 1 Mhz signal propagates. The students' attention is focused using a magnifier : only an elementary slice 30 cm long can be seen. The student then notes, that through the magnifier, he can only see one thousandth of the wavelength and that the field amplitude at a given time t is constant over the whole length of the slice. In the second animation, the signal frequency is multiplied by 100. The E and H fields amplitudes observed under the magnifier are no longer constant. In the third animation, the frequency is 1 Ghz and through the glass, the student notes that the field varies largely since the length of the elementary slice is the same as that of the wavelength. At this stage, the student immediately understands that, if he wants to use an electric circuit schematic of the low frequency type with constant lumped elements, he will have to consider elementary slices for which the field amplitudes remain practically unchanged, that is to say elementary slices which are much shorter than the wavelength. Thus, the cascading of elementary slices demonstrates to the student, in a natural way that it is possible to translate the propagation phenomenon.

b) The shift from electric et magnetic field notations to those of voltage and current

The problem is now to shift from field notations to those of voltage and current. Let us return to our elementary slice of waveguide made of two separate conductors carrying a T.E.M. mode, the electric field defined between the two conductors is constant all along the slice, as has previously been shown. The line integral of the electric field between the two conductors generates a voltage and the student is then asked to identify the circuit element (capacitor, inductor, resistance) that represents the structure.
Let us now define an elementary surface dS obtained by the product dz*L where dz represents the length of the slice and L the distance between the two conductors ; the magnetic field H, the amplitude of which is constant over dz is time-variable. The student immediately notes that the magnetic field normal to dS generates a time varying flux through dS, thus creating a self-inductive E.M.F (figure 3). The student can thus replace the elementary guide slice by an equivalent lumped electric circuit of the LC type and thus build his distributed elements schematic.

5) Terminated transmission line : simulations of various stationary wave regimes

First of all, to illustrate the idea of varying value impedance, the student is asked to go and "click" at different points on a charged transmission line. By doing so, he reveals the impedance representation in the corresponding plane along with its numerical value. Further in the course the student has the possibility to choose a load and obtain the corresponding standing wave mode representation on the line. The following exercise is proposed: we define a vector, the length of which represents the incident voltage on the load, and the student has to define the reflected one, thus he gives a numerical value to the load. The displacement on the line, from the load towards the generator results in a rotation of the two vectors in opposite directions. The vectorial sum is made at different points along the line and resultant vector amplitude is tabulated thus establishing the standing wave regime specific to this loaded line.

6) The Smith chart and its application

In the chapter on the Smith chart and its practical application, our aim is the following : the student must be able to redraw quickly and easily on the Smith chart any displacement or modification made on the line. Then, in the software, any displacement on the line and on the Smith chart is made synchronous. An analytic demonstration is given in the handbook explaining how the Smith Chart is built. In the software, numerous interactive exercises allow the student to become familiar with the Smith chart (figure 4). More complicated problems are proposed in synthesis exercises. For example, the determination of the impedance at a distance from the load or the impedance matching with a quarter-wave transformer or a simple stub are performed. In this type of exercise the student must choose the right solution to the problem in a series of multiple choice questions. For every wrong choice, a comment is always prompted to allow the student to understand and rectify his mistake.

CONCLUSION

We have designed a multimedia self-training introductory course package to microwaves. It is composed of a handbook and some interactive educational software which corresponds to about 20 hours of C.A.L.. At the present time, the English translation of the product is being undertaken.

We have presented some examples allowing the student to understand some basic concepts in microwaves. Undergraduate students of the university of Lille have tested this computer assisted learning tool and appreciated tackling this field in a manner different from the traditional approach, each at his own speed and with an attractive tool. Teaching staff also noted a greater curiosity on the part of the students, expressed by unusual questions they never asked for in a classical course, more motivation and a greater consolidation of their knowledge. This is due to the interactivity of the software and immediate correction of their errors.

This very positive experience has encouraged us to continue in this frame on a detailed study of waveguides such as rectangular metallic guide, coaxial line and microstrip.

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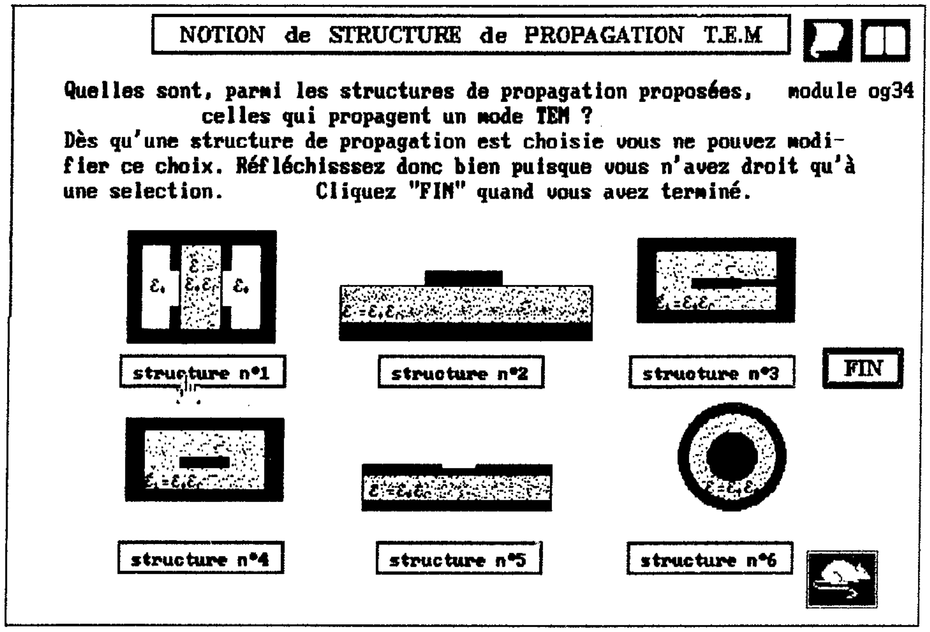


Figure 1 : Example of test : "Choose, among these structures of propagation, the ones that can propagate a TEM wave" .

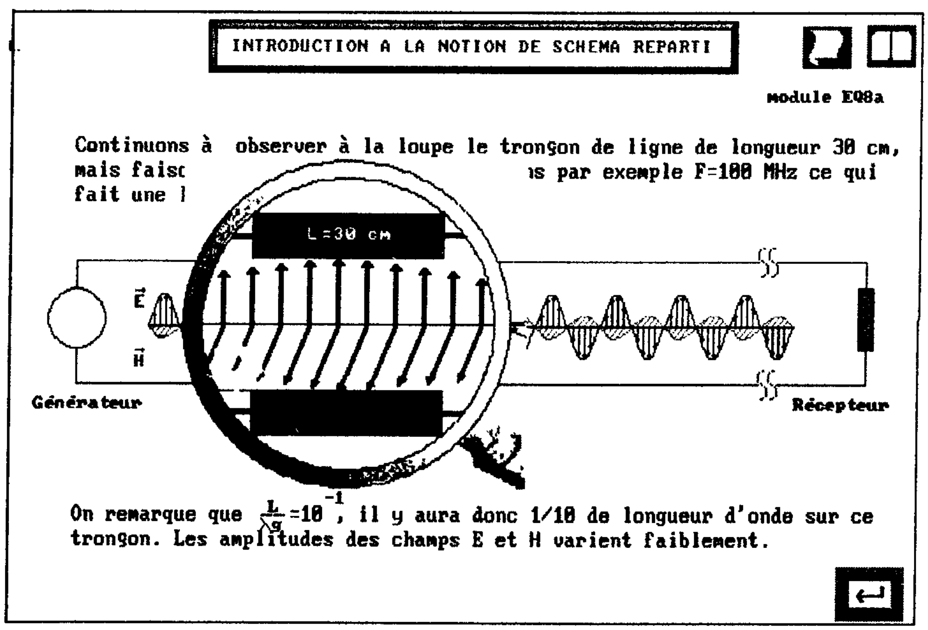
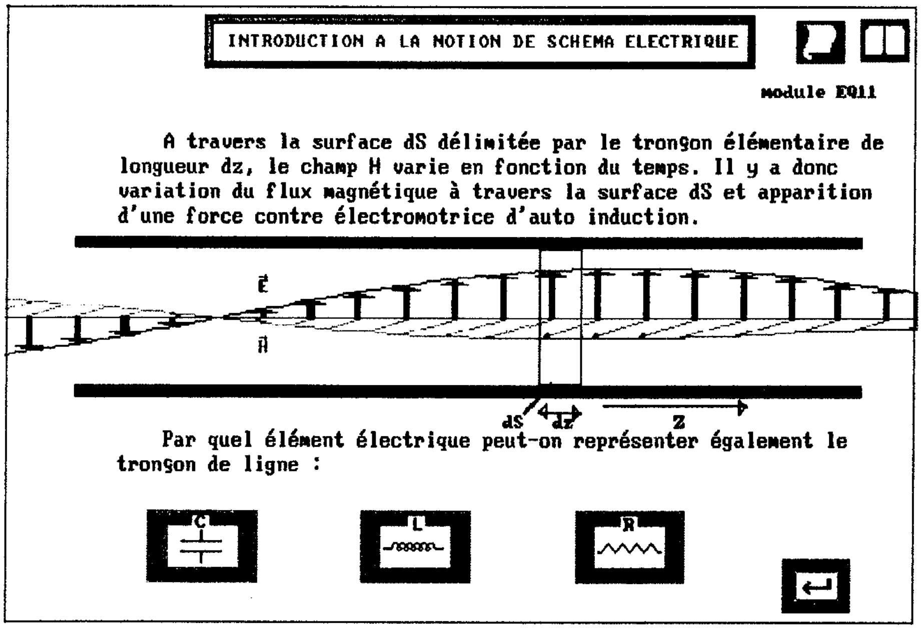
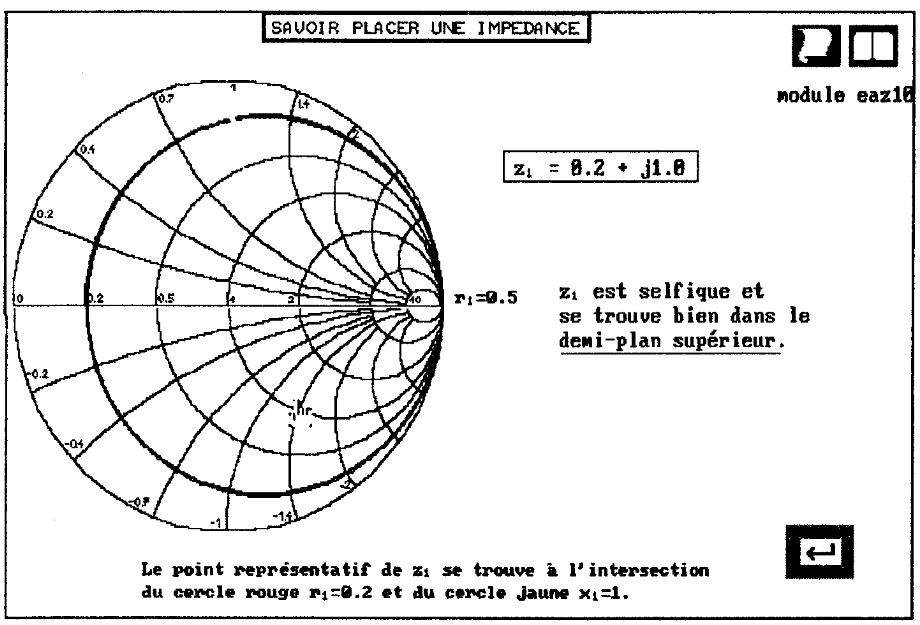


Figure 2 : Example of animation, showing the student, the evolution of a TEM wave on an elementary slice (L=30cm) of transmission line at frequency F=100Mhz.



<u>Figure 3</u> : Electrical equivalent circuit research of an elementary slice dz. Here, research of the inductance.



<u>Figure 4</u> : Test on the Smith chart : the student must point out the representative point of the normalised impedance z1.

EMAP: A 3-D, Finite Element Modeling Code for Analyzing Time-Varying Electromagnetic Fields

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Introduction

EMAP (ElectroMagnetic Analysis Program) is a three-dimensional finite element modeling code that was developed as a tool to be used for education and research. Like commercial finite element modeling codes, it solves for the field distribution in a variety of bounded, 3-dimensional geometries. Unlike commercial finite element modeling codes however, it is relatively easy to learn to use and it is distributed in source code form. EMAP can be used for student projects and demonstrations in undergraduate electromagnetics courses or in graduate microwave system courses. It is also a very useful laboratory aid for courses in numerical modeling techniques.

EMAP is not intended to compete with commercial codes. It does not have a sophisticated mesh generator, graphical output, or unlimited technical support. The purpose of the EMAP code is to provide an affordable tool that students can use to learn about electromagnetics and finite element modeling.

There are currently three versions of the EMAP code. EMAP-1 uses a variational formulation described by Maile [1]. EMAP-2 employs the Galerkin formulation described in papers by Paulsen and Lynch [2,3]. EMAP-2P is a parallel version of EMAP-2 designed to run on the Intel hypercube platforms. Each of these codes employ tetrahedral, first-order, nodal elements. The EMAP-1 code effectively demonstrates the problem of 'vector parasites' or 'spurious modes' that often arise in finite element modeling. EMAP-2 and EMAP-2P have been formulated to eliminate the vector parasite problem. EMAP-1 and EMAP-2 are written in 'C' and can be compiled and run on PCs, workstations, or mainframes.

The EMAP codes are readily available to educational and research institutions. They can be freely copied or distributed in unmodified form.

Structure of the EMAP code

The finite element mesh is defined on a cartesian grid using brick-shaped elements (hexahedra). The EMAP code automatically subdivides each hexahedron into five tetrahedra as shown in Figure 1. Linear functions of electric field strength with unknown coefficients at each node are the basic building blocks of the finite element solution. A matrix equation relating constants derived from the fixed (or constrained) node coefficients to linear functions of the unconstrained node coefficients is derived using one of the procedures outlined in the following sections.

The code is modular and both EMAP-1 and EMAP-2 follow the same basic solution procedure. A flowchart outlining the basic structure of the EMAP codes is provided in Figure 2. Specific

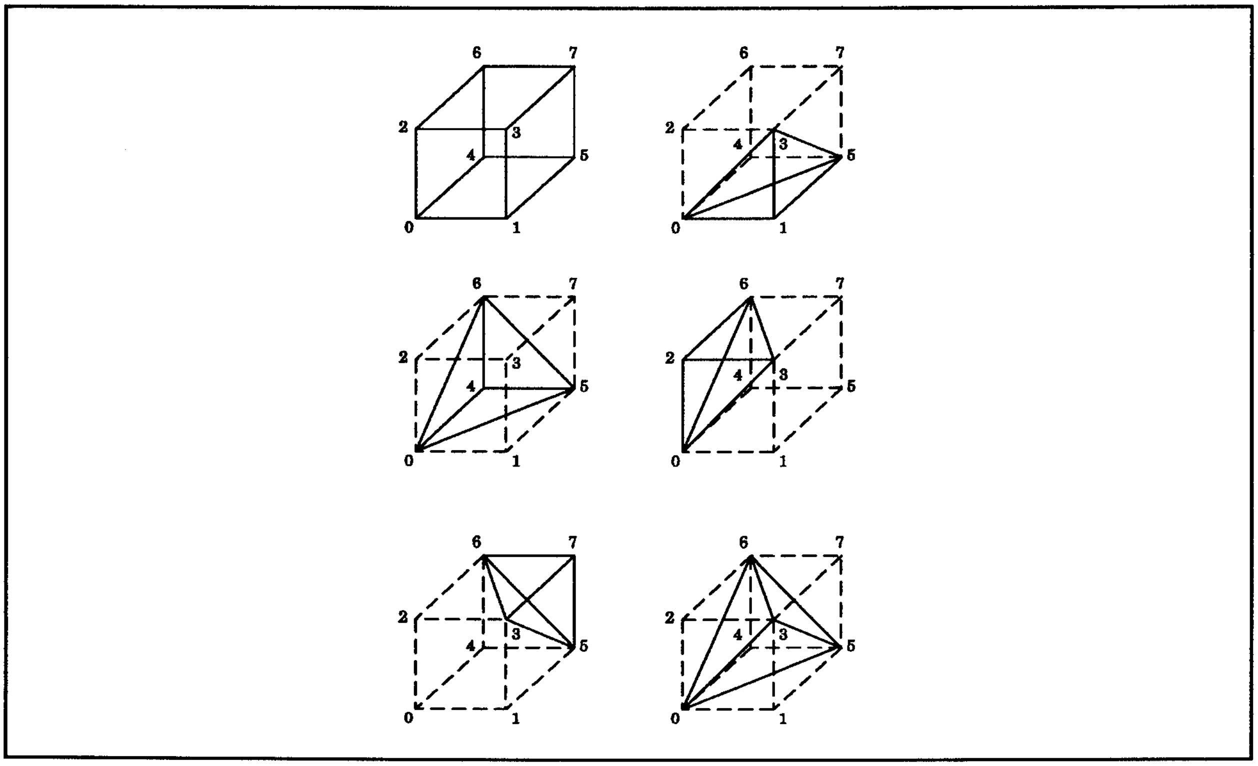


Figure 1: Division of hexahedron into 5 tetrahedra

subroutines are assigned to each task in the chart. Note that many subroutines are common to both EMAP-1 and EMAP-2. A brief description of each subroutine is provided below:

initialize	Reads the data input file and initializes variables.
no_of_hex	Calculates the number of hexahedra and number of global nodes.
assign.dim	Assigns to each node a global coordinate (x,y,z) and stores the result in the array asdnco[].
hex_nodes	Assigns each vertex of every hexahedra a unique global node number and stores the result in the array hexhed[].
div.hex	Divides a hexahedra into 5 tetrahedra and assigns node numbers based on connectivity. Node numbers are stored in the array tetrnod[].
vol.det	Calculates the volume determinant of the specified tetrahedron
cofac	Calculates the cofactors of the specified tetrahedron matrix
A.matrix	Calculates the tetrahedral matrix coefficients (12 x 12 matrix).
hex_max	Assembles the hexahedron matrix.
global.mat	Assembles the global matrix exploiting the sparsity to reduce the memory required.
cal.nodes	Determines which nodes are free, forced or boundary nodes and stores their node numbers in the arrays unodes[], fnodes[], and bfnodes[] respectively. Values of forced nodes are stored in the array forval[].

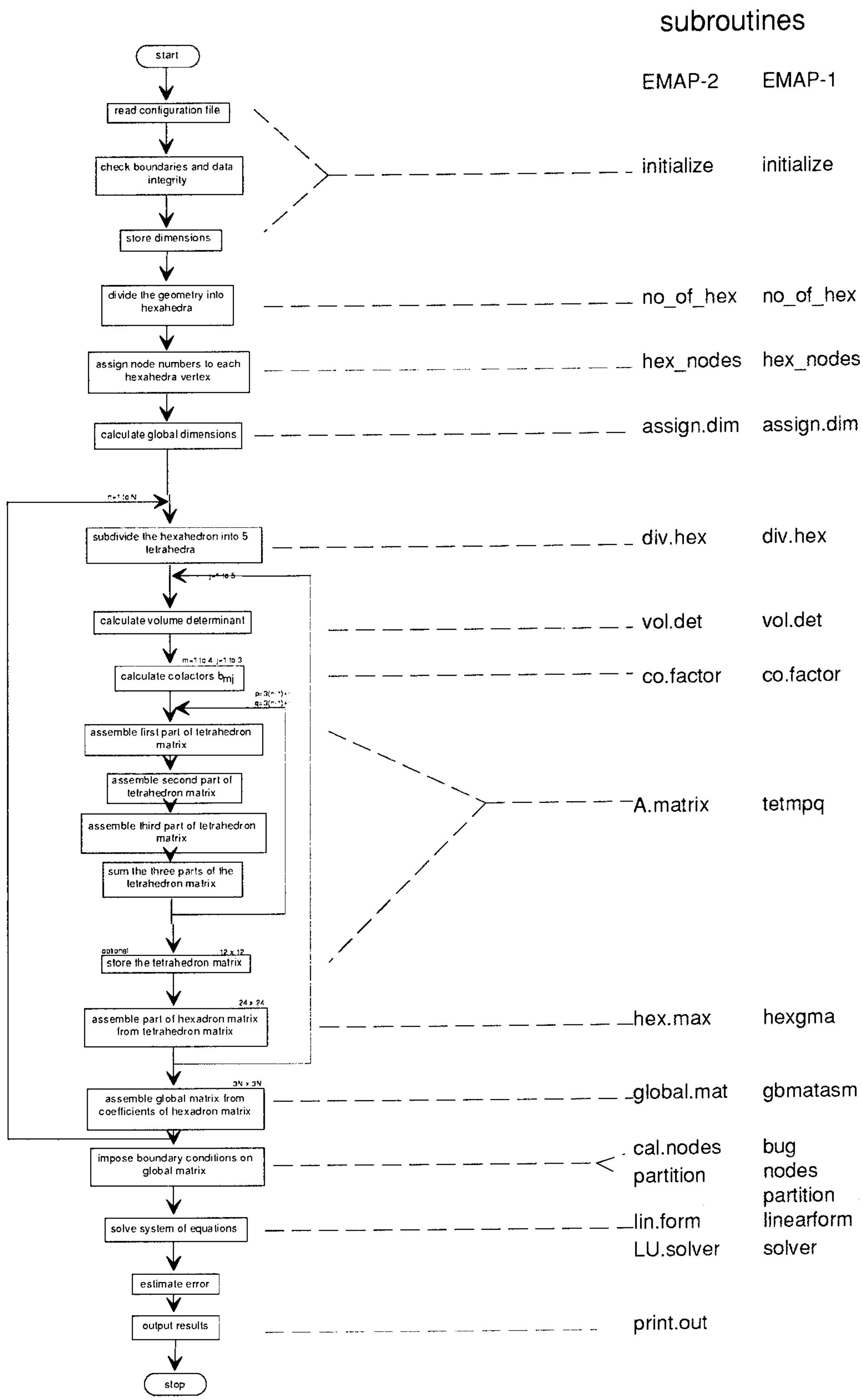


Figure 2: Flowchart for EMAP-1 and EMAP-2 codes

partition	Partitions the global matrix
lin.form	Prepares a matrix equation of the form Ax=B.
LU.solver	Solves the linear system of equations. Currently this is done using an LU-decomposition technique.
print.out	Formats and prints the electric field coefficients at each node.

EMAP-1 Formulation

EMAP-1 employs the variational formulation described by Maile [1]. Variational methods solve for the field distribution using a suitable *functional.* The functional is a function of the field distribution that is known to be stationary (i.e. has a minimum or maximum value) when the distribution is the *true* solution. Generally, the functional is an expression relating to the total energy in the configuration. The functional used by the EMAP-1 code is of the form,

$$F_E = \frac{1}{2}\int_v \varepsilon \left[E \cdot E^* - \frac{(\nabla\times E)\cdot(\nabla\times E^*)}{k^2} \right] dv \tag{1}$$

where E is the electric field distribution, ε is the permittivity of the material and k is the wave number ($k = \omega\sqrt{\varepsilon\mu}$). To determine the field distribution that minimizes this functional, this expression must be partially differentiated with respect to the vector components of E and the resulting expression set equal to zero. Using the procedures and notation of Maile [1], which is also described in the text by Silvester and Ferrari [4], the discretized partial derivative of the E-field functional in a tetrahedral element is given by,

$$\frac{\delta F_E}{\delta E_m^{(i)}} = \varepsilon V \left(\frac{1+\delta_{mn}}{20} \right) E_n^{(i)} - \frac{\varepsilon \left(b_{mj} b_{nj} E_n^{(i)} - b_{mk} b_{ni} E_n^{(k)} \right)}{36 V k^2} \tag{2}$$

where $E_m^{(i)}$ is the i^{th} component of **E** at the m^{th} vertex. i,j,k each take on values of 1,2,3 and m,n range from 1 to 4. V is the volume of the tetrahedron. b_{mj}, b_{nj}, b_{mk}, and b_{ni} represent cofactors of the volume determinant. The expression in Equation 2 is used to find the coefficients of a tetrahedron submatrix of order 12 (4 tetrahedron vertices x 3 vector field components).

Partial derivative coefficients are evaluated for each tetrahedral element. The tetrahedron submatrices are then assembled into hexahedron submatrices, which are subsequently assembled to form a global matrix. A matrix equation is then formed which equates these coefficients to zero, thus enforcing the stationary condition.

The global matrix at this point is singular. The system of equations cannot be solved until a sufficient set of boundary conditions is applied. This involves constraining the electric field at some nodes to take on a particular value. Generally, the tangential component of electric field is constrained to have a value of zero on metallic boundaries. Sources are included in the model by constraining the field at some nodes to take on a fixed non-zero value.

After imposing boundary conditions, the matrix equation can be put in the form **Ax=B** where **x** is a vector of coefficients describing the electric field at each unforced node. The coefficients of **A** and **B** are known functions of the problem geometry, mesh geometry and boundary conditions. Solving the matrix equation for **x** yields the coefficients necessary to describe the field distribution throughout the problem region.

EMAP-2 Formulation

EMAP-2 does not employ a variational method. Instead it applies a Galerkin method to solve a modified form of the vector Helmholtz equation introduced by Paulsen and Lynch [3]. The modified form below includes a term which explicitly enforces the condition that $\nabla \cdot \boldsymbol{E}$ must be 0 in a homogeneous medium,

$$\nabla \times \left(\frac{1}{j\omega\mu} \nabla \times \boldsymbol{E} \right) - \nabla \left(\frac{1}{j\omega\mu\varepsilon} \nabla \cdot \varepsilon \boldsymbol{E} \right) + j\omega\varepsilon \boldsymbol{E} = 0 \tag{3}$$

The expanded weak form of this equation used by the EMAP-2 code can be written as,

$$< \frac{1}{j\omega\mu} (\nabla \times \boldsymbol{E}) \times \nabla \varphi_i > + < \frac{1}{j\omega\mu\varepsilon} (\nabla \cdot \varepsilon \boldsymbol{E}) \; \nabla \varphi_i > + < j\omega\varepsilon \boldsymbol{E} \; \varphi_i > = 0 \tag{4}$$

where < and > indicate integration over the problem domain. φ_i are the basis functions associated with the Galerkin procedure (in this case the linear field distribution associated with each finite element).

Expanding **E** in terms of weighting functions φ_j such that,

$$\boldsymbol{E} = \sum_{j=1}^{N} E_j \; \varphi_j \tag{5}$$

and substituting for the electric field in Equation 3, results in an expression that can be written in matrix form as $A_{ij} \, E_j = 0$ where,

$$A_{ij} = \begin{bmatrix} < \frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta x} + \frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta y} + \frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta z} - k^2\varphi_j\varphi_i > & < -\frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta y} + \frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta x} > & < -\frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta z} + \frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta x} > \\ < -\frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta x} + \frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta y} > & < \frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta x} + \frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta y} + \frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta z} - k^2\varphi_j\varphi_i > & < -\frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta x} + \frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta y} > \\ < -\frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta x} + \frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta z} > & < -\frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta y} + \frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta z} > & < \frac{\delta\varphi_j}{\delta x}\frac{\delta\varphi_i}{\delta x} + \frac{\delta\varphi_j}{\delta y}\frac{\delta\varphi_i}{\delta y} + \frac{\delta\varphi_j}{\delta z}\frac{\delta\varphi_i}{\delta z} - k^2\varphi_j\varphi_i > \end{bmatrix} \tag{6}$$

The entries in this matrix can be expressed as functions of the tetrahedral element volume (V) and the corresponding cofactors (b_l, c_l, d_l) [5] resulting in the expression below,

$$A_{ij} = \begin{bmatrix} \dfrac{b_i b_j^T + c_i c_j^T + d_i d_j^T}{36V} - \begin{cases} 1/10 & i=j \\ 1/20 & i \neq j \end{cases} & \dfrac{-b_i c_j^T + c_i b_j^T}{36V} & \dfrac{-b_i d_j^T + d_i b_j^T}{36V} \\ -\dfrac{c_i b_j^T + b_i c_j^T}{36V} & \dfrac{b_i b_j^T + c_i c_j^T + d_i d_j^T}{36V} - \begin{cases} 1/10 & i=j \\ 1/20 & i \neq j \end{cases} & \dfrac{-c_i d_j^T + d_i c_j^T}{36V} \\ \dfrac{-d_i b_j^T + b_i d_j^T}{36V} & \dfrac{-d_i c_j^T + c_i d_j^T}{36V} & \dfrac{b_i b_j^T + c_i c_j^T + d_i d_j^T}{36V} - \begin{cases} 1/10 & i=j \\ 1/20 & i \neq j \end{cases} \end{bmatrix} \tag{7}$$

Assembly of the hexahedron matrices and global matrix proceeds in the same manner as EMAP-1. In fact, although EMAP-1 and EMAP-2 are very different in terms of their solution method, only two subroutines are significantly different in the two codes. The subroutines that calculate the cofactors and create the tetrahedral submatrix are necessarily completely different. The subroutines that read the data, define the elements, and assemble and solve the matrix equation are virtually identical.

One additional difference between EMAP-1 and EMAP-2 is that the EMAP-2 code permits the electric field to be discontinuous at a dielectric boundary. This feature significantly improves the codes' ability to model configurations with dielectric interfaces. The procedure used is similar to that described by Paulsen [6]. Nodes on a dielectric interface are effectively split in two during the initial stages of the algorithm. Each half of the split node is in a different dielectric. During the final stages of the global matrix assembly, the halves are recombined and the discontinuity in the normal electric field is explicitly enforced.

```
0
0
0
10
0
0
0
5
0
10
5
0
0
0
15
10
0
15
0
5
15
10
5
15
0 0 0 0 0 0 1 0
1 0 0 0 0 0 1 0
2 0 0 0 0 0 1 0
3 0 0 0 0 0 1 0
4 0 0 0 0 0 1 0
5 0 0 0 0 0 1 0
6 0 0 0 0 0 1 0
7 0 0 0 0 0 1 0
8 0 0 0 0 0 1 0
9 0 0 0 0 0 1 0
10 0 0 0 0 0 1 0
0 1 0 0 0 0 1 0
1 1 0 0 0 -2 1 0
2 1 0 0 0 -2 1 0
•
•
•
1 5 15 0 0 0 1 0
2 5 15 0 0 0 1 0
3 5 15 0 0 0 1 0
4 5 15 0 0 0 1 0
5 5 15 0 0 0 1 0
6 5 15 0 0 0 1 0
7 5 15 0 0 0 1 0
8 5 15 0 0 0 1 0
9 5 15 0 0 0 1 0
10 5 15 0 0 0 1 0
```

Header

node-by-node description

Figure 3: Sample data input listing

Data Input and Output

The EMAP codes read data in as an ASCII text file and print data out in the same form. This allows the source code to remain free of non-standard graphical I/O commands or routines. As a result, the EMAP source code is highly portable and has been run on a variety of platforms without modification.

The basic format of the input data is a short header followed by a list of the mesh node coordinates. A sample input file is illustrated in Figure 3.

Because it can be difficult and time consuming to create an error-free data input file for 3-D configurations, a translation code has been written that allows the user to draw the input configuration using a commercial com-

puter aided drawing program. DesignCAD 3-D [7] is a powerful, but relatively easy to learn CAD program that can be used to generate fairly complex 3-D geometries. The translation code reads the DesignCAD output file and creates an EMAP data input file. The translation code associates DesignCAD grid points with mesh nodes. Colors in the CAD drawing are used to represent different material properties and arrows are used to provide excitation sources [8].

The DesignCAD interface has proven to be an invaluable aid for creating and verifying input configurations. DesignCAD 3-D runs on PCs and Macintoshes and is available to educational institutions at a nominal charge. It is also possible to develop translation codes for other CAD programs running on other platforms. In many cases, the effort involved in writing a new translation code is less than the effort required to learn to use a non-standard graphical interface.

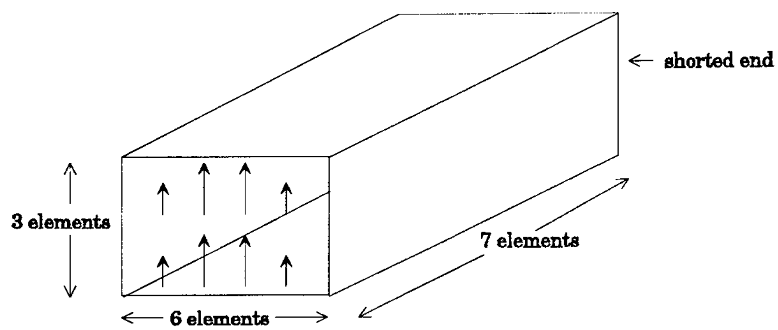
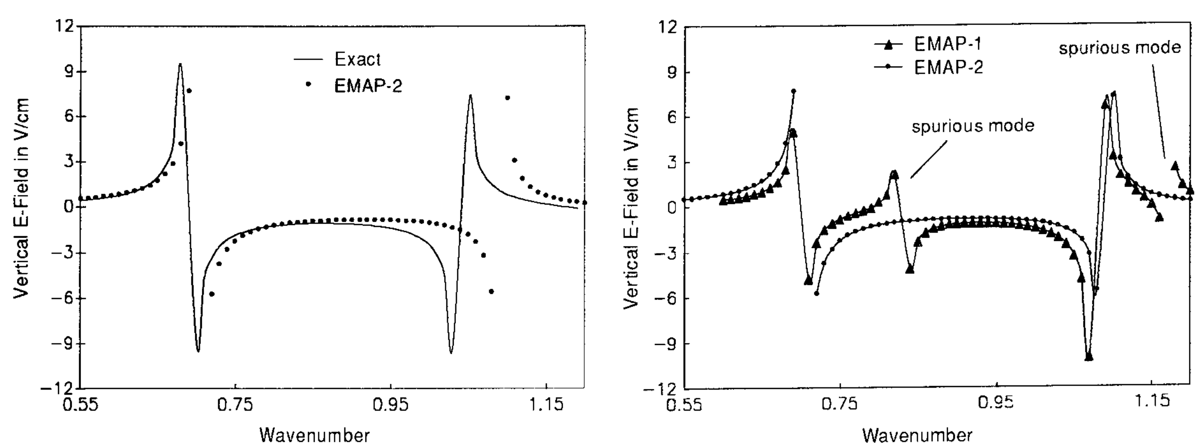


Figure 4: Shorted, air-filled waveguide of Example 1



(a)

(b)

Figure 5: Field at a point inside the waveguide

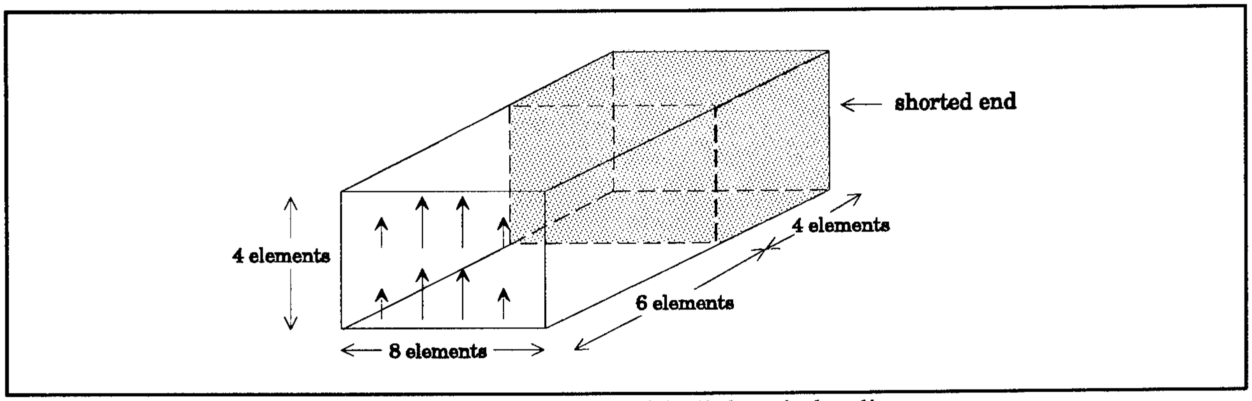


Figure 6: Waveguide with dielectric loading

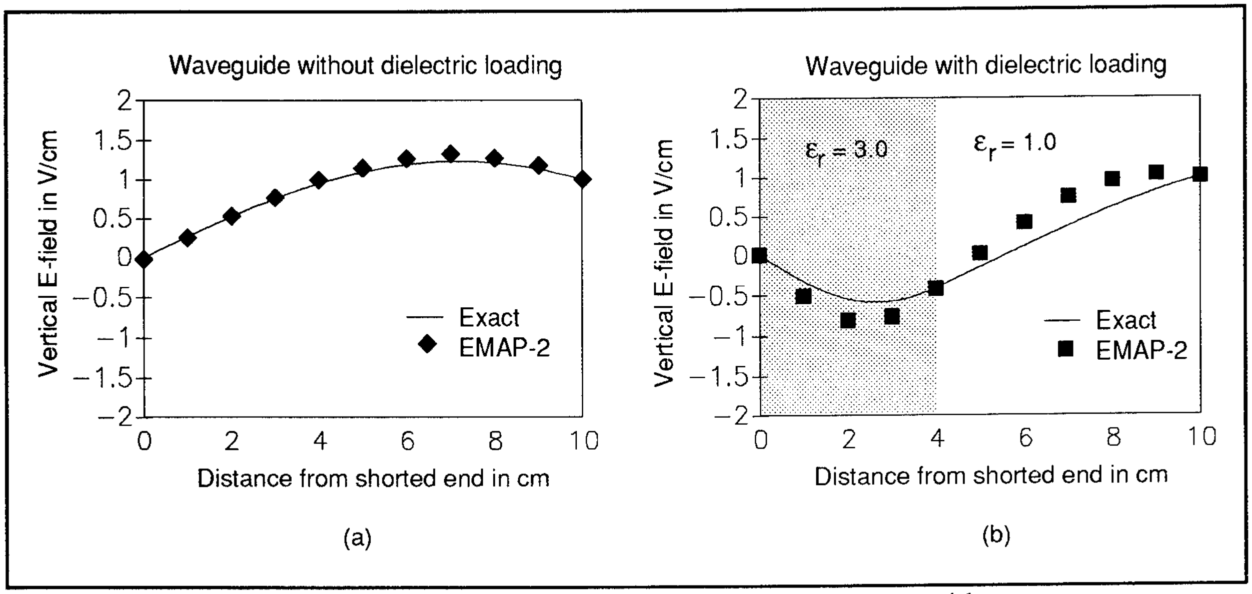


Figure 7: Vertical E-field in dielectric loaded waveguide

Output from the EMAP code consists of a listing of the node coordinates and the electric field strength at each node. This data can be easily read by a variety of spreadsheet programs and rearranged, plotted, or manipulated as desired.

Examples

As an illustration of how the EMAP codes can be used, two sample configurations are analyzed below. The first configuration is a TE_{10} wave propagating in an air-filled waveguide shorted at one end (see Figure 4). Despite the relatively crude finite element mesh and the small number of elements used to model this configuration, fairly good agreement is obtained between the EMAP-2 calculated field and an exact analytical calculation as shown in Figure 5a. This figure shows the vertical electric field at a point 3 cm away from the shorted end as a function of wave number, k. Note that the frequency of the first resonance shown is predicted very accurately even though at this frequency each element is 1/7th of a wavelength long. At the second resonance, where each element is greater than 1/5th of a wavelength, there is understandably significant error. A finer mesh is required to analyze this structure at these higher frequencies. Figure 5b compares the EMAP-2 results with the results from EMAP-1. Spurious modes in the EMAP-1 results are clearly observed.

This configuration is particularly prone to spurious modes at the higher wavenumbers where modes other than TE_{10} are supported.

The second sample configuration is the dielectric loaded waveguide illustrated in Figure 6. This waveguide is also shorted at one end and driven in the TE_{10} mode. The vertical electric field strength is plotted as a function of position along the center of the waveguide in Figure 7. With or without the dielectric loading, there is very good agreement between the finite element model and analytical results calculated using standard transmission line theory.

Conclusions

The EMAP codes have been developed to fill a need for an easy-to-learn and use, 3-D electromagnetic finite element modeling code. EMAP is primarily intended for use in education, but the technique is powerful enough for a variety of applications.

EMAP-1 is a variational formulation exhibiting spurious mode phenomena, while EMAP-2 is a Galerkin formulation that is immune to spurious modes. Both versions are distributed in source code form and run on a variety of platforms. These codes are available by anonymous ftp from *emclab.ee.umr.edu*. In the near future, they should be available on diskette through the Applied Computational Electromagnetics Society (ACES) and the Center for Computer Applications in Electromagnetics Education (CAEME).

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A ROMANIAN EXPERIENCE IN COMPUTER-AIDED ELECTROMAGNETIC EDUCATION

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Abstract

The paper presents the actual interests in computer-aided electromagnetic education (CAEE) at the Electrical Engineering Department from Polytechnic Institute of Bucharest, Romania.

The actual state of computer use on different levels of undergraduate and graduate education is presented. Specifically, an overview of the undergraduate theoretical training and practical applications is described, and research topics for graduate reports and doctoral dissertations are discussed. Issues related to hardware utilities are reviewed, and future projects aimed at improving the CAEE capabilities in Romania are described.

The material is based on significant selected references.

1. Introduction

The Polytechnic Institute of Bucharest is the oldest and most dominant engineering school in Romania. With a history of more than one hundred years, the Institute is composed today of several departments, including Electrical, Mechanical, and Chemical Engineering, Computer Science, Materials Science, etc. [1].

The Electrical Engineering Department is organized to train about 250 graduates (M.S. engineer equivalent) and 5-10 postgraduates (Ph.D. equivalent) a year in domains such as electromechanical devices, electrophysics, electrotechnologies, electrical drive systems, measurement, and management.

The history of the computer impact in engineering education started approximately 25 years ago with the study of the programming language Fortran. The applications were possible on an old IBM-1130, the first computer at the Polytechnic Institute of Bucharest and several Hewlett-Packard "computing machines," which seem to be very old fashioned now but released a lot of passions among students at that time.

Year by year, the importance given to computers in education increased, so that it became usual to find homework, current projects, and especially graduation reports and doctoral theses having a strong numerical basis.

This paper presents the actual state of computer use on different levels of education at the Electrical Engineering Department from the Polytechnic Institute of Bucharest. The relevant educational software packages in the CAEE area developed in this department are presented.

2. Fundamental Grounding

The undergraduate studies in the Electrical Engineering Department covers 10 terms, each of 14 weeks length of time. The timetable covers weekly 30 hours on an average (about 50% lectures and the other 50% applications: laboratories, seminars, and projects). Usually, the curriculum offers about 75 disciplines, 45 of them being compulsory and 5 at the student's choice. The last term is dedicated to the completion of the graduate final report.

Of great interest for CAEE are the following branches:

- mathematics
- physics
- computer science
- fundamentals of electromagnetics
- electronics
- electrical apparatus, machines, and drive systems.

The **mathematical disciplines** are studied during the initial three terms and in about 420 teaching hours (lectures and seminars). These studies cover a large area including: linear algebra, geometry, analysis, complex functions, vector field analysis, integral and differential equations, and integral transforms.

Physics is studied during the initial five terms and its main topics are: mechanics, statistics and thermodynamics, quantum mechanics, fluid flow, and materials science.

Computer science study has the following stages:

- *computer programming* -- the Pascal language is studied during the first and second terms, in 42 lecture hours and 56 laboratory hours
- *programming techniques* -- during the third term (28 lecture hours and 14 laboratory hours), the students are initiated in data structures and non-numerical algorithms (pointers, lists, stacks, ques tries, graph finding and sorting techniques, etc.)
- *numerical methods* -- in the fourth term (42 lecture hours and 14 laboratory hours), the main numerical algorithms with specific applications in electrical engineering (linear equation systems, interpolation and approximation of functions, nonlinear equations and systems, numerical derivation and integration, ODE, and PDE)
- *digital systems* -- in the fifth term (28 lecture hours and 14 laboratory hours)
- *microprocessor programming* -- (28 lecture hours and 14 laboratory hours) in the fifth term
- *Microprocessor systems* -- structure and functions are studied in the eighth term (42 lecture hours and 28 laboratory hours).

Fundamentals of **electromagnetics** with the main interests in:

- *electrical circuits* -- (84 lecture hours and 70 application hours) during the third and fourth terms
- *electromagnetic field* -- in the fourth and fifth terms (84 lecture hours and 42 application hours), the study is directed to Maxwell's equations and the specific time dependencies for EM fields
- *system theory* -- studied during the fifth term (42 lecture hours and 28 application hours).

The most relevant course in this stage is "Numerical Methods in Electrical Engineering" [4, 5]. Despite it being at an introductory level, this course combines elements of numerical analysis, programming techniques, and methods for computer analysis of electric circuits and electromagnetic fields. For the laboratory associated with this course, the Electrical Engineering Department developed a computer-aided learning package named **NUMEE** (Numerical Methods in Electrical Engineering). This package contains 25 lessons and covers the following topics:

- *numerical algorithm analysis and mathematical data structures* (error propagation, complexity of the algorithms, abstract data types, etc.)
- *algebraic linear systems* (Gauss method, pivoting strategies, LU decomposition, sparse matrix techniques, iterative methods) with application to the linear electric DC and AC circuit analysis
- *approximation and interpolation* (polynomial interpolation: Lagrange, Newton, Thebishev, piecewise polynomial interpolation: spline, Bessel, Akima, least square approximation)
- *function derivation and numerical integration* (divided differences of different orders, backward, forward or central, integration by trapezoidal, Simpson, Romberg, Gauss methods)
- *nonlinear equation solving* (Newton, Picard, secant methods, etc.) with application to the DC nonlinear electric circuits
- *ordinary differential equations* (implicit and explicit Euler method, Runge-Kutta) with application to the transient linear and nonlinear electrical circuit analysis
- *partial differential equations* (FDM -- finite difference method, FEM -- finite element method, and BEM -- boundary element method) with application to the static electric and magnetic fields
- *circuits and system numerical techniques* (Fourier transform, eigen values and vectors).

The laboratory class is carried out by students' practical participation. Each laboratory work begins with the execution of an illustrative program whose input data are entered by the student; e.g., solution of the Laplace equation by RDM in a square using Dirichlet boundary conditions (Fig. 1), solution of the Poisson equation by the REM in a circle using Dirichlet boundary conditions (Fig. 2), and computation of the electrostatic field generated by two plane parallel electrodes in free space using BEM (Fig. 3).

The program steps through the algorithm pointing out the effect of each step upon the initial data (e.g., the convergence of numerical solution in iterative process). The second part allows an estimate of the computing effort and accuracy of the algorithm using a standard set of input data (e.g., the computing time vs. the node numbers of the grid). The exact solution is compared against the numerical results. During the third step, the student must translate into Pascal the pseudocode algorithm from the laboratory guide and implement a short test program which solves a precisely defined simple problem. The last phase in the laboratory work consists of an automatic knowledge test.

The **NUMEE** has been developed in Turbo C environment and contains about 30,000 C lines. It can be run on an IBM PC or compatible computers. The educational experience gained using **NUMEE** is very encouraging. Contrasting to the study of a textbook, the students' interest in such a learning approach is higher.

3. CAEE Experience in Undergraduate Education

On the second stage of study, students begin to face the main engineering-like disciplines with an important applied nature, namely the electronic circuits and devices, electromechanical devices, and drive systems.

The area of **electronics** consists of:

- *electronic devices* -- in the fifth term (28 lecture hours, 14 seminar hours, and 28 laboratory hours)
- *electronic circuits* -- in the sixth term (56 lecture hours, 28 laboratory hours, and 28 design hours)
- *electric and electronic measurements* -- in the sixth term (42 lecture hours and 42 laboratory hours)
- *power electronic devices* -- in the sixth term (28 lecture hours and 14 laboratory hours)
- *power electronic circuits* -- in the seventh term (42 lecture hours and 28 laboratory hours).

The main topics in the **electromechanical** discipline are:

- *electrical machines* -- in the sixth and seventh terms (112 lecture hours and 84 laboratory hours)
- *electrical apparatus and devices* -- in the sixth and seventh terms (112 lecture hours and 70 laboratory hours)
- *electrical drive systems* -- in the seventh and eighth terms (84 lecture hours and 84 application hours: seminar, laboratory, and design).

The ordinary training in different domains is completed by several optional disciplines. The undergraduate students perform homework and terminal projects. Some of them prefer to integrate in their works small codes, created by themselves on personal computers or one the department computers available to them. The most usual problems treated in that way are:

- electrical circuit problems
- material properties simulations
- optimization criteria in design of electric machines and apparatus
- several design methodologies, usually the iterative ones
- simulation of different working conditions of drive systems
- statistical or graphic postprocessing of experimental measurements.

The quotation system for student work encourages these sorts of computer applications, because they require both a proper and adequate formulation of the EM problem and the finding of the right numerical method to solve it. At the same time, we noticed a remarkable increase in self confidence and an appetite for improvement in computer knowledge. The references used are classical ones and include specific textbooks, such as [2, 3, 4, 5].

The coordination of several term projects on electrical machines (d.c. motors, power transformers) is partly organized based on computer codes with the following structure [9, 10]:

- preprocessing of some specific data (the project subject)

- development of a design methodology for main electromagnetic and geometric estimate
- economic optimization, if necessary
- electromagnetic field computation
- postprocessing of results: working characteristics, graphic representations.

Many courses deal with electric/magnetic circuits simulated in different working conditions with linear or nonlinear elements. The specific code **RESEL** developed in the E.E. Department to solve this problem [11] has the following features:

- a description of the network topology using a **SPICE**-like language
- a description of the initial state and time-dependent supply sources
- postprocessing of the results: graphic presentation of any electric/magnetic signals.

Microprocessors in drive systems is one of the most application-oriented topic in EM education. Its laboratory and term projects are actual applications of digital control positioning systems [8]:

- design and implementation of control procedure
- numerical simulation of positioning systems
- implementation of digital control system (software and hardware architecture) with practical applications on a Z80 microprocessor.

4. CAEE Experience in Graduation and Doctoral Dissertations

Most graduate students and all doctoral students in engineering who have presented dissertations during the last 10-15 years paid great attention to computer applications on their EM problems. Here are some of the most important and recently elaborated topics:

(1) Electric and magnetic 2D and 3D field analysis associated with different geometric structures such as power transformers, electric machines (d.c. and a.c.), high-voltage insulators, high-current switches, devices used in technologies of composite materials, electrothermal systems, electrochemical devices, etc. [9, 13, 14, 15, 18].

The general structure of such dedicated codes allows:

- input data-geometry of domain, initial and boundary conditions, description of field sources and material properties
- numerical treatment of specific field equations and boundary conditions (finite difference, finite element, integral form methods and hybrid methods are frequently used)
- solution of large linear or nonlinear algebraic system of equations
- postprocessing of solutions: computation of losses, energy, mechanical stresses, field line representations, evaluation of electric and magnetic circuit parameters, etc..

(2) General CAD/CAE packages, easy to use in design work, combining the design methodologies with EM field and circuit problems and the economical optimization in problems like electronic analog and digital circuits, power apparatus, electric machines, drive systems [12, 13, 15, 18].

(3) Dynamic answer of electromechanical systems based on Fourier transform spectral methods [16, 17]:

- electrical measurements with signal processing
- nondestructive diagnosis of failures in high-power transformers and electric machines
- monitoring techniques and diagnosis of drive systems.

One relevant package, initially developed as a graduate requirement, is the "Field Analysis Program -- **FAP**" [19, 20]. This software package is dedicated to education in the CAD/CAE area. **FAP** allows analysis of the two-dimensional field in linear media, being characterized by the Poisson equation with a Dirichlet, Neumann, or Robin boundary condition using the finite-element method. The programs run on an IBM PC/XT/AT and compatible computers and have a strongly interactive user interface. **FAP** may be applied to the electric, magnetic, and thermal field analysis in different devices. It consists of:

FPR -- graphic preprocessor
FED -- problem editor
FCL -- linear problem solver
FDO -- graphic postprocessor.

The programs are chained by a driver named **FAP**, thus creating an integrated environment.

The problem to be solved is described in an interactive way, using the graphic preprocessor **FPR** and problem editor **FED**. In **FPR** the geometric and topological data is inputted. Automatic and manual grid general is allowed. Each homogeneous domain is identified by an alphanumeric label and represented on screen using a specific graphic pattern. **FED** allows the input of source and material values associated to a different label used in **FPR** (Fig. 4).

The following commands are available in the preprocessing stage:

The problem solver **FCL** uses the geometric and topological data generated by the graphic preprocessor and the physical values given by the problem editor to generate the linear equation system specific to the finite-element method. The system matrix is a sparse one, and a special storage technique is used. The linear equation system is solved using either the SOR method or conjugate graduate method. Since the solver uses dynamic memory allocation, the problem size is limited only by the available computer memory. On a 640-KB IBM PC, problems can be as large as 5000 elements. The **FPO** postprocessor uses geometrical data from the **FPR** preprocessor, and the solution given by the solver **FCL** allows the obtaining of an image of the analyzed device as well as a wide variety of output options. This includes (Fig. 5):

- local values of potential, field strength in magnitude, modulus, and by components
- integral values on curves/surface like electric or magnetic flux
- global values like energy, force, and torque computed or specified domain
- graphical representation of the solution along the user-defined line segment
- 3D graphical representation of the solution.

The software package **FAP** was successfully used in education. It allows the modeling of electric and magnetic devices such as actuators, electric machines, electrochemical devices, magnetic shielding problems, etc. (Fig. 6).

Unfortunately, in the Polytechnic Institute of Bucharest there is no organized form of postgraduate courses for the Ph.D. candidates. There is also no form of long-term or continuous postgraduate education. With the object of exceeding this stage, a TEMPUS project entitled, "Initiation of Formal Training in Computer-Aided Electrical Engineering in Romanian Universities" and coded JEP 2717, is granted by the European Community. The main goal of this Joint European Project is to establish a postgraduate school containing a training and documentation center in the area of CAD/CAE, both for electromechanical devices and for electronic circuits, including VLSI circuits. The institutions involved in this project are: Politecnico di Torino, Institute National Politechnique de Grenoble, University of Bath, Universita di Genova, Universita di Cassino, Universite de Paris, and Technische Universitat Graz.

The first year of the project, 1991-92, is dedicated to the organization of the Training Center: laboratory design, equipment and CAD software purchase, selection of teachers, language courses, and mobility of Romanian professors to EC countries for retraining and updating. The activities during the subsequent two years will include the beginning of the training, computer-aided learning software development, mobility for the Training Center's students, and mobility programs for foreign professors teaching in Romania.

The postgraduate training center will have two main directions of study: electromagnetic fields and electric/electronic circuits. A team at the Polytechnic Institute of Bucharest continued the development of a CAL package for numerical methods in order to enhance its suitability for the needs of postgraduate education.

5. Hardware Utilities

The recent surpassed historical period for the Romanian society -- the communist dictatorship -- was very unfavorable to the extent of the modern electronic utilities, especially the computational equipment. This happened in a moment of spectacular revolution of the world technical level.

That is why, at the beginning of 1990, the majority of the computers in use at the Polytechnic Institute of Bucharest were microcomputers on 8 bytes with 8080 or Z80 microprocessors, Sinclair compatibles, or using the old operating system CP/M. Many of these were bought through considerable personal effort by the professors and were made available to the students. Some IBM-PC compatible systems were far from satisfying the demands. The Polytechnic Institute of Bucharest, an institution with over 28,000 students, even now does not have the capability to use powerful Unix workstations. Starting with 1990, the development of several projects with the purpose of improving computing utilities has begun [7].

The Department of Electrical Engineering acquired, at the beginning of 1990, around 40 IBM-PC/AT compatible microcomputers, the majority coming from the Far East, with the main performances: CPU 8088; 1 MB RAM; 20 MB HDD, 1.2 MB FDD, Hercules monochrome graphics card.

In 1991, the department acquired 3 Novell LANs with 12 terminals each, dedicated to specific class applications for students in the early years. The networks are made up of a file server IBM PS/2 386 and IBM PS/2 model 30 terminals; the operating system is Netware 3.11 + DOS 3.3.

In 1992, there are several new projects under consideration:

- **DFN-Verein** project, which consists of the making up of a local network interconnecting the three campuses of the Polytechnic Institute of Bucharest. The infrastructures will be made of optic fiber, which allows a future increase on information transfer. Through the TCP/IP protocol, it will be possible to include the Novell cluster and other terminals. This project is a joint venture between the Polytechnic Institute of Bucharest and the Technical University of Darmstadt. It has a budget of 373,000 DM, most of it coming from the German government.

- The acquisition of Unix workstations is another important need for the Polytechnic Institute of Bucharest. The lack of experience in this domain makes it difficult to choose the proper solutions. This is why the decision made for the moment provides for the acquisition of several types of workstations for the practical testing of their capabilities in correspondence with our working conditions. This way, it will also be possible to gain experience with hybrid networks. To start with, the following types for "entry-level" workstations were chosen:

  DEC Station 5000/25
  HP Apollo Workstation 9000/710
  HP-X Station 700
  Sun IPX
  Sun ELC
  Silicon Graphics -- Indigo
  IBM RS 6000/320H

  In 1993, the network will be extended with file servers and stations which proved to be most advantageous. This project is funded by the TEMPUS JEP 2717 budget.

Two other projects planned for future years are:

- **RUN** -- Romanian University Network, which deals with the network connection among the main Romanian universities

- **RRDN** -- Romanian Research and Development Network, which deals with the network connection among over 60 national research institutes and universities.

The main purpose of these projects is to connect Romania and its powerful potential in education and research to the international academic networks. In this case, the Polytechnic Institute of Bucharest will be the central national node and the front end of the international network.

6. Conclusions

In this paper, a variety of EM topics that interest us were discussed and the practical results which are obtained from our experience in computer-aided education were described. These efforts resulted directly from the enthusiasm, desire to learn, and desire for self improvement of our teachers and students. The theoretical background of our faculty and students is very powerful, while the available technical utilities (software and hardware) are far from satisfactory.

We also consider that a better organization of documentation would be very useful, and an improved distribution mechanism would both benefit the users (educational as well as research communities) and have a favorable impact on the promotion of successful research projects.

During the last several years, we have more and more signals from research and industry media that encourage us to insist on CAEE education for a better integration of our graduates in electrical engineering life as well as for the development of mutual research projects between academia and industry.

The experience gained until now (through the TEMPUS projects) shows clearly that one of the most important elements that ensures the success of educational projects is the cooperation between universities having the same professional interest. Therefore, we welcome new partners in our TEMPUS JEP and are open to cooperation with other higher educational projects in the CAEE area.

Acknowledgments

The authors would like to thank the Department of Electrical Engineering administration and all the colleagues who encouraged this paper and helped in information storage and systematization.

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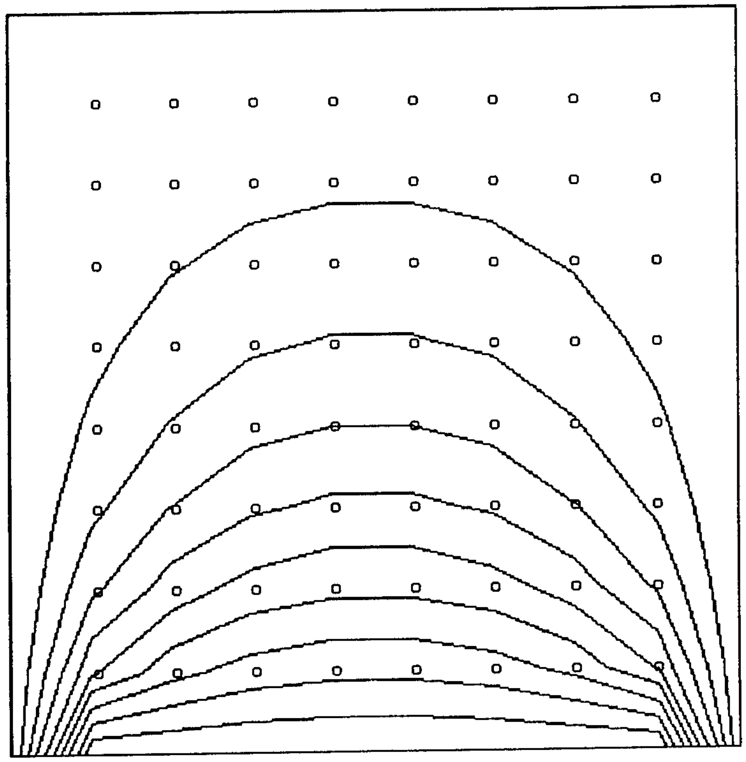

Fig. 1. Equipotential lines obtained by FDM.

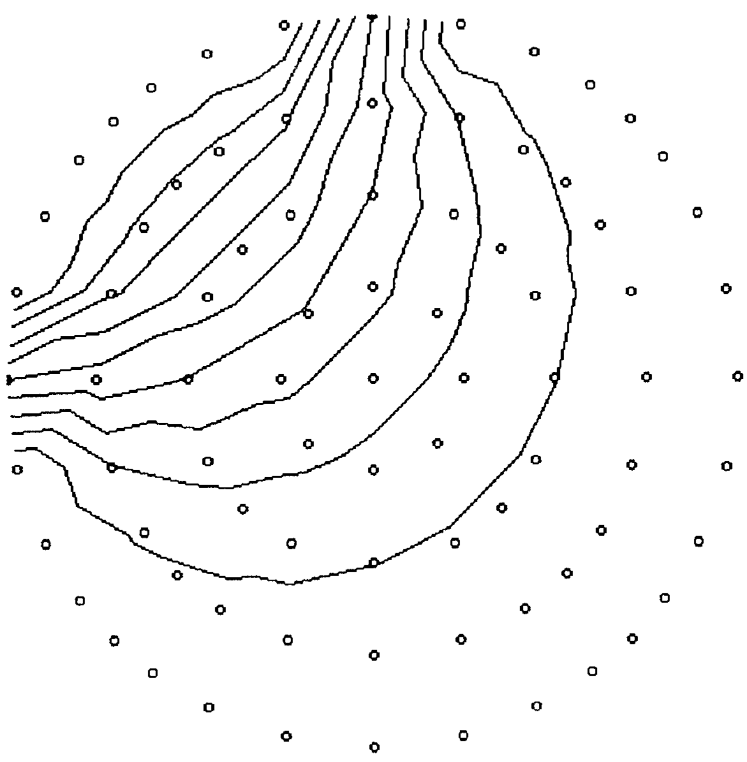

Fig. 2. Equipotential lines obtained by FEM.

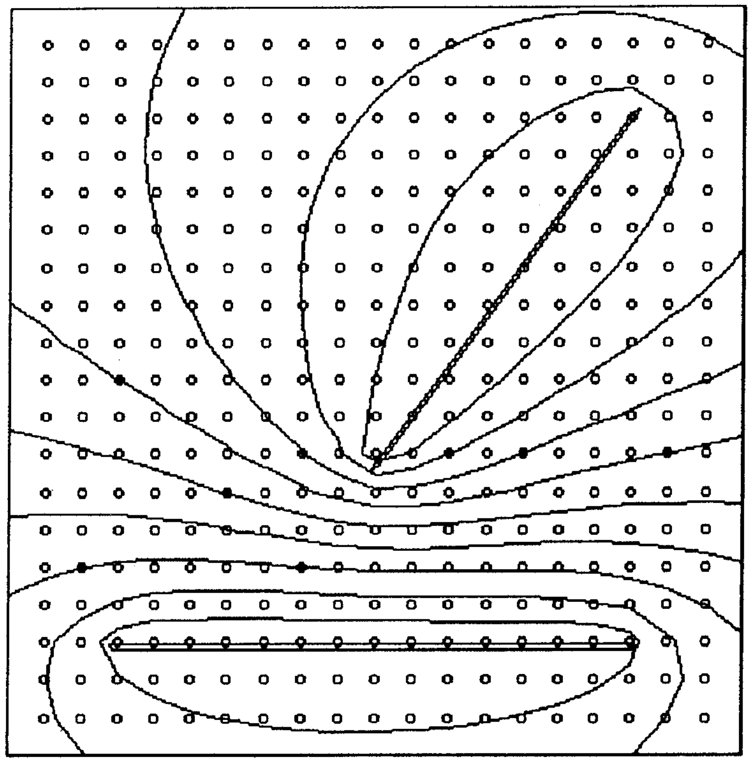

Fig. 3. Equipotential lines obtained by BEM.

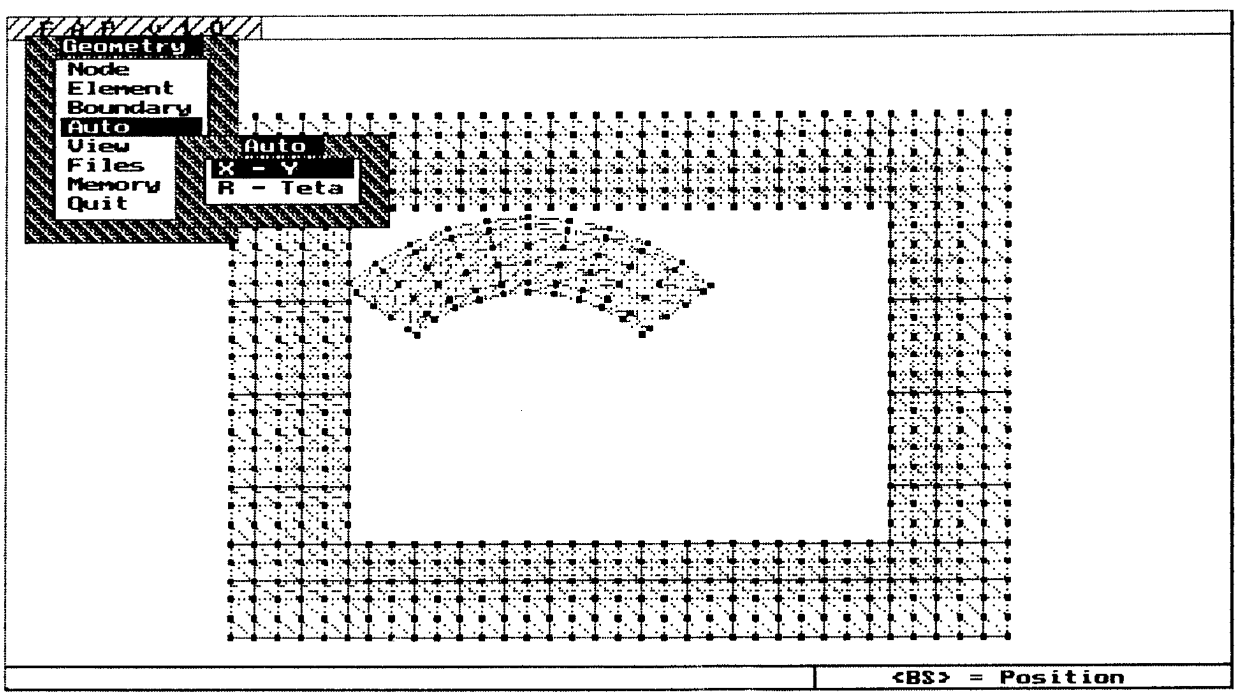

Fig. 4. Automatic mesh generation.

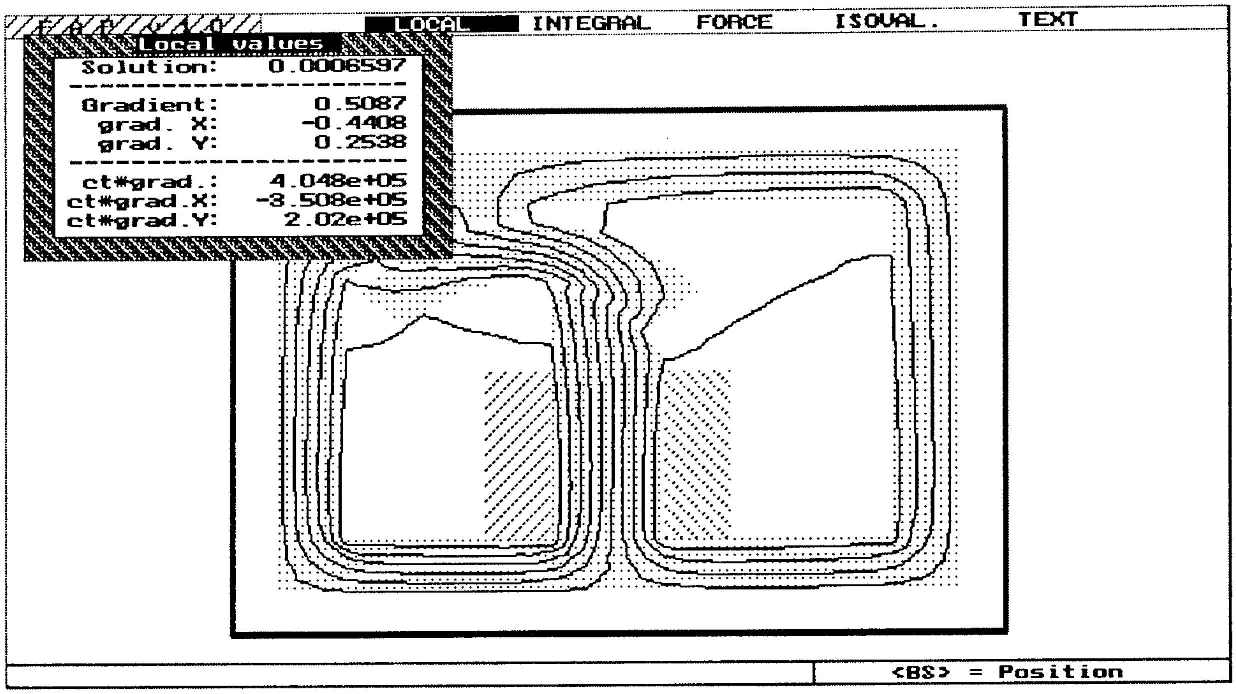

Fig. 5. Postprocessor screen sample.

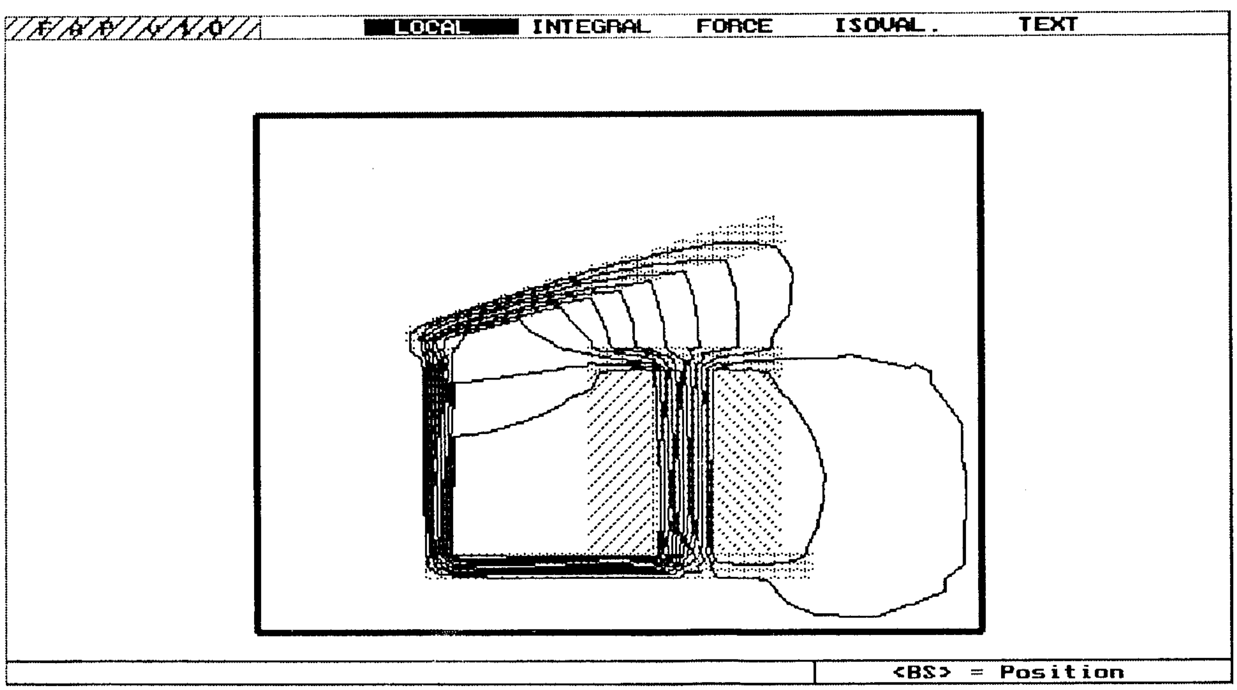

Fig. 6. Magnetic field lines of an actuator.

CAL - Antennas
Computer-Aided Learning of Antennas

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ABSTRACT

CAL-ANTENNAS is a tool containing graphics (2D and 3D) and sounds coded in the Turbo Pascal 5.5 language, for the implementation of educational software on antennas. From the Units files, a data base (frequency bands, antenna forms, antenna dimensions, formulae, characterising radiation) and a repertory of numericals methods (integration, graphs plotting, etc...) have been developped, complying with speed contraints. The necessary fundamental principles are contained in text files. Thus, this is one of the first structured software packages developed on the computer in the domain of antennas that treats the fundamental principles and the methodology of design.

This version of CAL-ANTENNAS for the microcomputer based on the Intel 386 and 486 Microprocessors contains more than a hundred illustrations.

1. INTRODUCTION

CAL-ANTENNAS is a teaching as well as a design tool. Several programs exist [2] - [4] , [9] - [10] for the computer-aided study of either one type of antenna or one specific application of antennas. This software on the other hand is a structured book on antenna in a microcomputer. This version of the software for microcomputers based on the Intel 386 and 486 microprocessors is written in Turbo Pascal 5.5.

This software is meant first for student of higher education, since it is at that level that courses on antennas are generally taught. CAL - ANTENNAS may then be used effectively as a support.

This software is also meant for general and technical high school students, who will then be able to :

- make a classification of electromagnetic radiation,
- name antennas,
- determine the frequency ranges corresponding to each type of antenna based on what has been presented in several works [2] - [8].

Finally, this software is meant for radio-amateurs who will then be able to dimension their antennas.

CAL-ANTENNAS is a software comprising two main parts :

- an enterily illustrated course on antennas,

- a part to enable one to dimension antennas and to determine their characteristics following theories presented in several reference works [2] - [5]

2 . THE MAIN MENU

The main menu has five options :

Help, Lesson, Design, Reference, Exit.

Once you type ANTENNA, the display on the screen is :

Help	Lesson	Design	Reference	Edit

[ ] [ ]

<Esc> = Previous Menu	Up, Down, Left, Rigth = Options	<Enter> = Val

2.1 The MENU Help

This menu gives the user information on CAL-ANTENNAS commands. This will help him get acquainted with the software.

As soon as you validate the option Help, you fall on the first help page. To move into the next page you must depress the <Enter> key. To get out of the Help menu you press the <Esc> key.

The choice of an option can be made in two ways:

- by typing the initial of the option chosen,
- by depressing one of the following keys: -->, <--.

The choice can also be carried out with the keys: Up, Down.

The validation of an option is made by depressing the <Enter> key.

- <Enter> enables you to move onto the next page.
- <Esc> enables you to exit and return to previous option.

In the exercices sub menu, the Fl key enables you to have the computer answer; the F2 enables you to make the demonstration.

2.2 The MENU Lesson

The menu Lesson is an illustrated course and exercices on antennas. The course is made of different parts. Each part is directly accessible. To make it easy to understand the course, each part is illustred by a sketch. Once lesson is selected, the display on the screen is the following:

Help Lesson Design Reference Exit

LECTURE
EXERCICES

1°) The sub Menu Lecture

Once Lecture is selected, the display on the screen is the following :

Help Lesson Design Reference Exit

LECTURE

I. History
II. Radioelectricity
III. Antennas

(i) If the choice is I - History, you have on the screen the history of the means of the communication whose illustrations are reproduced in figures 1 to 8. Figure 2 reflects african cultures, which shows the adaptability prospects of the software CAL-ANTENNAS.

(ii) If the choice is II- Radioelectricity, the display on the screen is the following:

Help Lesson Design Reference Exit

LECTURE

I. History
II. Radioelectricity

1 - Recalling
2 - Classification
3 - Propagation of waves
4 - Frequency Spectrum

Each option allows you to gain direct access to a given part of the lesson on radioelectricity. For example, option 2. Classification gives you the classification of electromagnetic radiation. Figures 9 to 15 are some of the illustrations of this part of the lesson on radioelectricity.

(iii) If the choice is III - Antennas, the display on the screen is the following:

Help | Lesson | Design | Reference | Exit

LECTURE

I. History
II. Radioelectricity
III. Antennas

1. Definition
2. Principle
3. Characteristics
4. Attenuator and repartioner
5. Types of antennas

The options 1 - Definition and 4 - Attenuator and repartitioner enable you to gain direct access to two parts of the lesson. Illustration of this options are shown in Figures 16 to 18.

On the other hand, each of the other three options has a submenu.

(★) If the choice is 2 - Principle, the display on the screen is :

Help | Lesson | Design | Reference | Exit

LECTURE

I. History
II. Radioelectricity
III. Antennas

1. Definition
2. Principle

a. Fields
b. Polarization
c. Radiation Pattern
d. Half wave length antenna
e. Ground effect
f. Excitation of antenna

Figures 19 to 28 reproduce some of the illustrations of the lesson on the principle of antennas. The supply of an antenna is illustrated by Figures 24 to 28, taking into account the many possible cases of this principle. That also is CAL-ANTENNAS, an evolutionary data bank.

(★★) If the choice is 3 - Characteristics, the screen shows :

Help | Lesson | Design | Reference | Exit

LECTURE

I. History
II. Radioelectricity
III. Antennas

1. Definition
2. Principle
3. Characteristics

a. Radiation Resistance
b. Efficiency
c. Bandwidth
d. Beamwidth
e. Directivity Gain
f. Radiation Power Gain
g. Effective Length
h. Apparent Radiation Power
i. Matching of an antenna

Figures 29 to 37 illustrate the part of the Lesson dealing with the characteristics of antennas. Each of these is accompanied in CAL-ANTENNAS by appropriate explanations.

(★★★) If the choice is 5- Types of antennas, the screen shows :

Help | Lesson | Design | Reference | Exit

LECTURE

I. History
II. Radioelectricity
III. Antennas

1. Definition
2. Principle
3. Characteristics
4. Attenuator and repartitioner
5. Type of antennas

a. T antenna
b. Vertical radiator
c. Log-periodic antenna
d. Helical antenna
e. Quarter wavelength vertical antenna
f. Yagi antenna
g. Pyramidal horn antenna
h. Parabolic refector antenna
i. Microstrip antenna

CAL-ANTENNAS illustrates a few types of antennas as reproduced here in Figures 38 to 47. With this software it is possible to complete and/or improve these illustrations if necessary.

2°) <u>The sub Menu Exercices</u>

Once Exercices is validated, the display on the screen is the following :

<table>
<tr><td colspan="2">Fundamental   Dipoles   Aperture   Reflectors   Microstrips</td></tr>
<tr><td></td><td></td></tr>
<tr><td>PgUp=Previous   Fl=Answer
Pgdown=Next   F2=Explanation
Fl0=Exit</td><td><Enter> = Introduce your answer</td></tr>
</table>

(★) If the choice is <u>Fundamental</u>, the display on the screen is for example :

<table>
<tr><td colspan="2">Fundamental   Dipoles   Aperture   Reflectors   Microstrips</td></tr>
<tr><td>Exercice 1
Give Maxwell equations</td><td></td></tr>
<tr><td>PgUp=Previous   Fl=Answer
Pgdown=Next   F2=Explanation
Fl0=Exit</td><td><Enter> = Introduce your answer</td></tr>
</table>

(★★) If the choice is <u>Dipoles</u>, the display on the screen is for example :

<table>
<tr><td colspan="2">Fundamental   Dipoles   Aperture   Reflectors   Microstrips</td></tr>
<tr><td>Exercice 1
A lossless resonant half-wavelength dipole antenna, with input impedance of 73 ohms, is to be connected to a transmission line whose characteristic impedance is 50 ohms Assuming that the pattern of antenna is given approximately by $U=B_0\sin^3 O$; Find the overall gain.</td><td></td></tr>
<tr><td>PgUp=Previous   Fl=Answer
Pgdown=Next   F2=Explanation
Fl0=Exit</td><td><Enter> = Introduce your answer</td></tr>
</table>

The user can introduce his answer. If the answer is correct, he will be congratulated. Otherwise he will be asked to try again. If the user can't find the solution, he can use the Fl key to have the computer answer, or the F2 key for the computer demonstration of the exercice.

2.3 The MENU Design

The Menu Design utilizes known theorical developments [1] - [4], [7], [8], [11] to characterize a given type of antenna. CAL-ANTENNAS may thus be considered as a complement to the many works that do not give numerical applications of the theory and/or do not illustrate the latter with appropriate sketches. The menu Design proposes, for the frequency range chosen, the corresponding antenna. It is also determines its characteristics and its dimensions. When you validate the option Design, the screen shows :

```
Help          Lesson          Design          Reference          Exit
                              APPLICATIONS
                              MEASUREMENTS
```

1°) The Sub Menu Applications

When you validate the option Applications, the screen shows :

```
Help          Lesson          Design          Reference          Exit
                              APPLICATIONS
                                  I. Frequency range
                                 II. Type of antenna
                                III. Dimensions
                                 IV. Characteristics
```

Following the choice of the option you get a display of the frequency ranges and the wave lengths for the corresponding band. For example, (i) if your choice is 1 - Radio - broadcast bands, the display on the screen is that shown in the Figure 48.

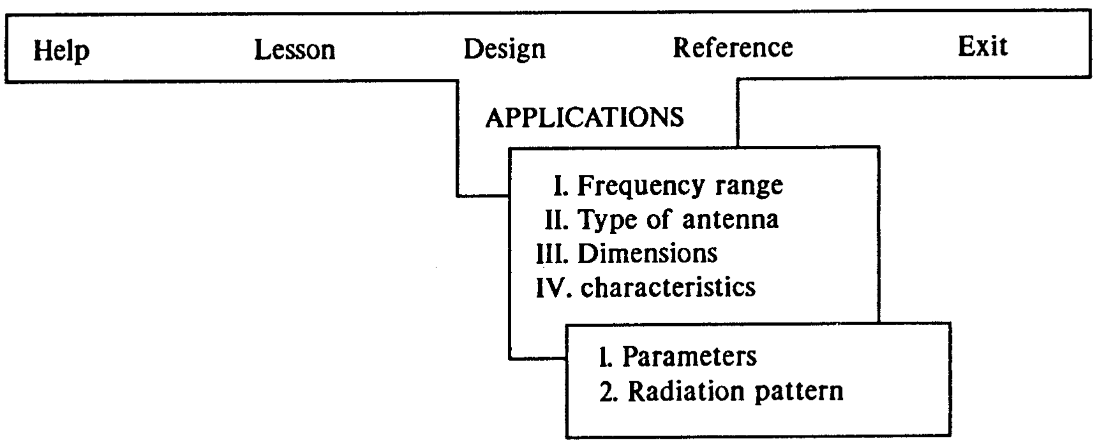
```
Help          Lesson          Design          Reference          Exit
                              APPLICATIONS
                                  I. Frequency range
                                      1. Radio - broadcast bands
                                      2. Tropical bands
                                      3. Radio-amateur bands
                                      4. Short-waves bands
                                      5. TV - FM
```

The validation of the frequency range sends you directly back to the preceding screen display. Thus you can see the type of antenna that correspond to the frequency range chosen.

(ii) if the choice is II - Type of antenna, the screen shows the antennas that correspond to the frequency range chosen. A message will be displayed if a frequency range has not be chosen before hand. The set of Figures (48, 49, 50) and (51, 52, 53) illustrates the choice of a frequency band as well as the type of antennas associated with it. Once validated, the antenna chosen is shown on the screen on a large scale.

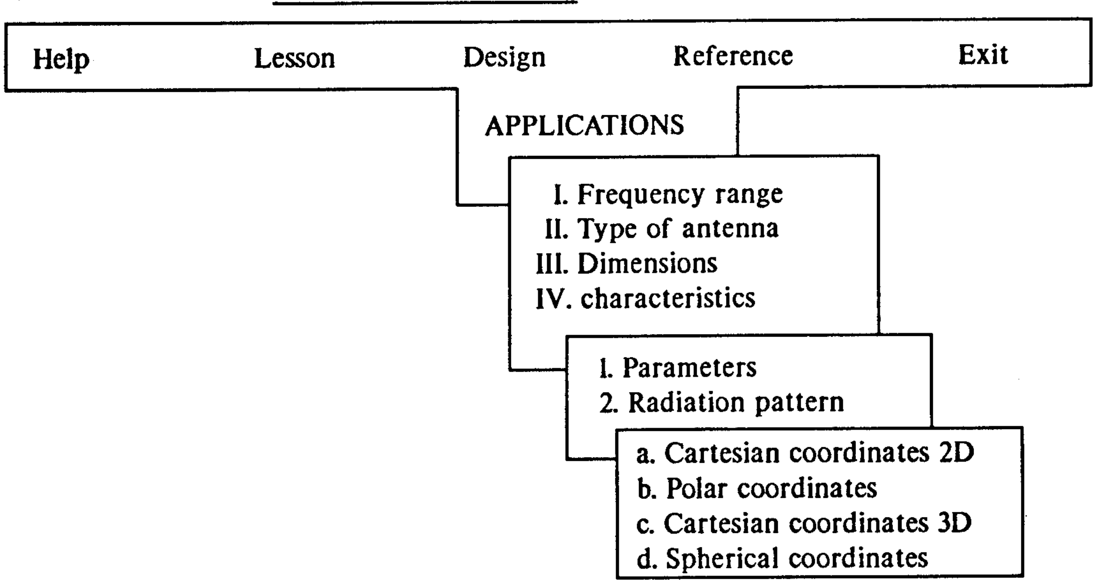
(iii) If the choice is III - Dimensions, you have on the screen the antenna chosen and its dimensions. Figures 54 and 55 are illustration samples.

(iv) If the choice is IV - Characteristics, the screen shows :



(★) If the choice is 1 - Parameters, you have on the screen the parameters (Bandwidth, Radiation Power, Directivity, Radiation Resistance) of the antenna chosen. This is illustrated in figures 56, in the case of successive choices of Figures 48, 49 and 54.

(★★) If the choice is 2 - Radiation Pattern, the screen shows:



For each option the radiation pattern of the antenna chosen is drawn in one of the four coordinate systems. Figures 57 to 72 are illustrations for T, helical, pyramidal horn and quarter wave vertical antennas respectively.

2°) <u>The Sub Menu Measurements</u>

This is not ready in this version of CAL-ANTENNAS.

2.4 <u>The menu References</u>

Once References is validated, the display on the screen is the following :

Help Lesson Design Reference Exit

REGISTRATION
RESEARCH

(⋆) If the choice is <u>REGISTRATION</u>, the display on the screen is :

Help Lesson Design Reference Exit

REGISTRATION

Book
Journal
Paper
Software
Video tape

(⋆⋆) If the choice is <u>RESEARCH</u>, the display on the screen is :

Help Lesson Design Reference Exit

REGISTRATION
RESEARCH

Book
Journal
Paper
Software
Video tape

Once Book is validated in the research menu, the display on the screen is for example the following :

Author : KRAUS J.D Title : Antennas Year : 1988, 892p Editor : McGraw-Hill (2nd)	Summary : 18 chapters ; Introduction, Basic antenna Concepts, Point sources, Arrays of points sources, ..., Antenna measurements.
Author : BALANIS C. A. Title : Antenna theory ; Analysis and design Year : 1982, 790p Editor : Harper and Row	Summary : 15 chapters ; Antennas, Fundamental parameters of antenna, ..., Antenna measurements.

2.5 The MENU Exit

It is the menu that enables you to get out of CAL-ANTENNAS.

3 CONCLUSION

CAL-ANTENNAS has five menus which are :

- Help, - Lesson, - Design, - Reference, - Exit

The menu Help gives the CAL-ANTENNAS commands.

The menu Lesson is a microcomputer aided course. It is a course which may be used by a teacher to illustrate a course on antennas: it is a teaching tool.

The menu Design enables one to know, for each frequency range, the characteristics of the corresponding antenna. It is of interest to:

- the teacher who will be able to use it as teaching material,
- the student who will be able to name antennas, give their characteristics and establish a correspondence between type of antenna and frequency range.
- the radio-amateur who would like to build his own antenna.

The menu References is a data base of antennas bibliography.

The prospects for CAL-ANTENNAS are the following :

- to improve the quality and the quantity of the data bank of illustrations,
- to complete the part lesson by adding exercices, as well as books, video cassette, and software references, including photos.
- to transform CAL-ANTENNAS into CAL-ANTENNAS and PROPAGATION in order to deal in more details with the topic of free and guided propagation.
- to take into account particular applications: radar, micro-wave heating, etc.

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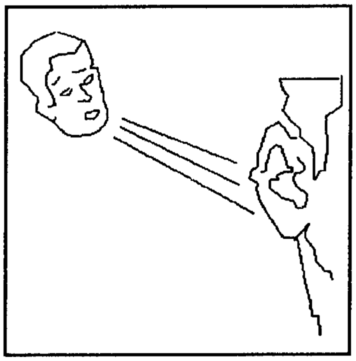

Figure 1 The mouth to ear conversation

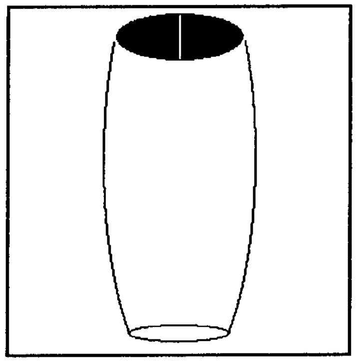

Figure 2 The drum

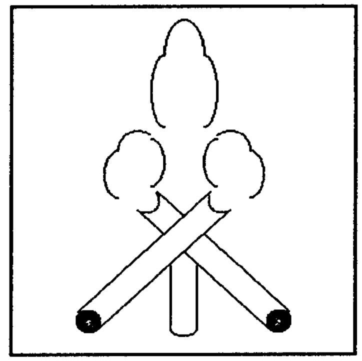

Figure 3 The smoke signals

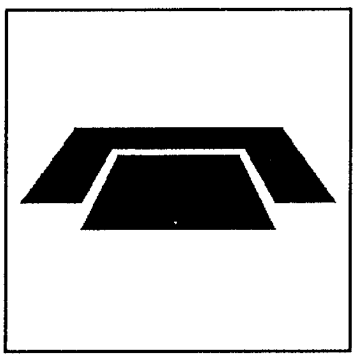

Figure 4 The telephone

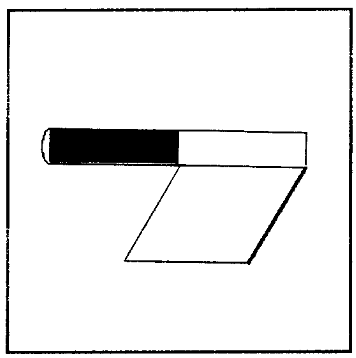

Figure 5 The pennant

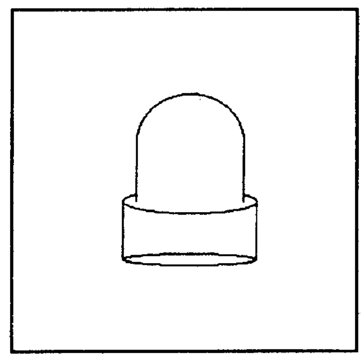

Figure 6 The blinking light

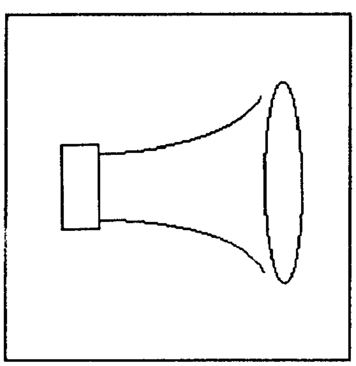

Figure 7 The siren

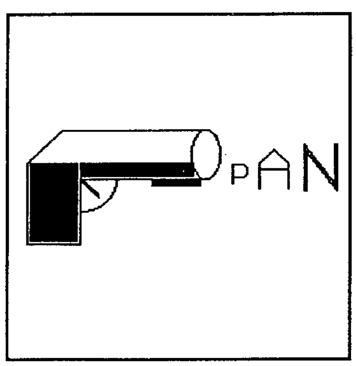

Figure 8 The pyrotechnical signals

Wave	LAMBDA	Frequencies	
decakilometrical	from 100 to 10 km	from 3 to 30 kHz	VLF
kilometrical	from 10 to 1 km	from 30 to 300 kHz	LF
hectometrical	from 1 to 0.1 km	from 0.3 to 3 MHz	MF
decametrical	from 100 to 10 m	from 3 to 30 MHz	HF
metrical	from 10 to 1 m	from 30 to 300 MHz	VHF
decimetrical	from 10 to 1 dm	from 0.3 to 3 GHz	UHF
centimetrical	from 10 to 1 cm	from 3 to 30 GHz	SHF
millimetrical	from 10 to 1 mm	from 30 to 300 GHz	EHF

Figure 9 Classification of electromagnetic waves

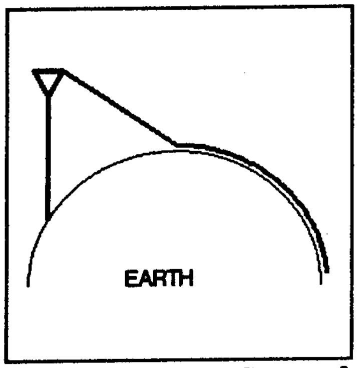

Figure 10 Ground wave

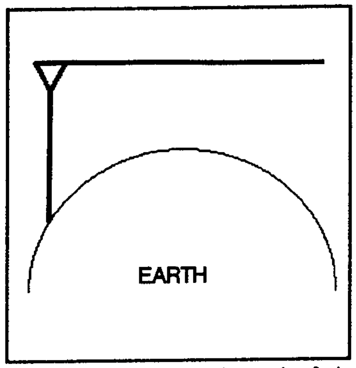

Figure 11 Straight line wave

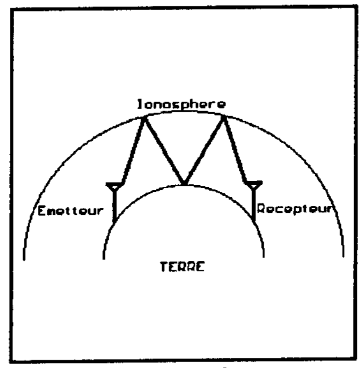

Figure 12 Sky wave

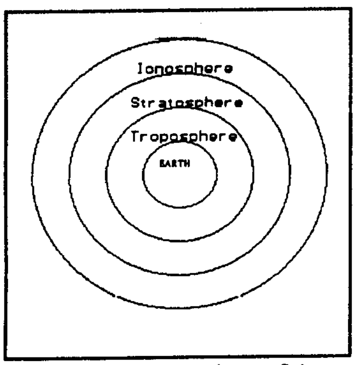

Figure 13 Medium of propagation of electromagnetic waves

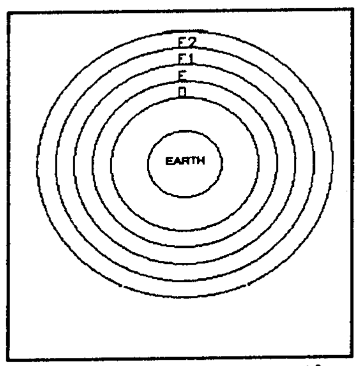

Figure 14 The zones of ionosphere

49	m	:	5 950	-	6 200	kHz
41	m	:	7 100	-	7 300	kHz
31	m	:	9 500	-	9 900	kHz
25	m	:	11 650	-	12 050	kHz
21	m	:	13 600	-	13 800	kHz
19	m	:	15 100	-	15 600	kHz
16	m	:	17 550	-	17 900	kHz
13	m	:	21 450	-	21 850	kHz
11	m	:	25 670	-	26 100	kHz

Figure 15 Frequency allocation : short-waves bands

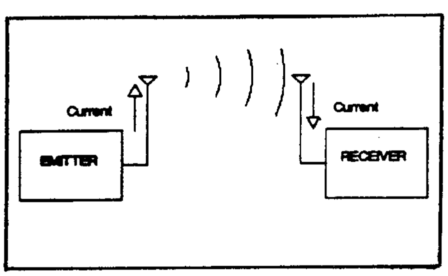

Figure 16 Emission /Reception of electromagnetic waves

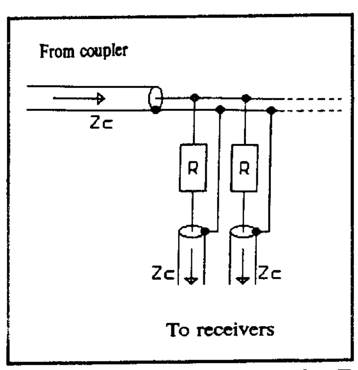

Figure 17 Distributor

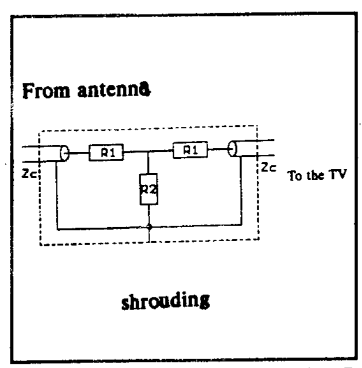

Figure 18 Attenuator

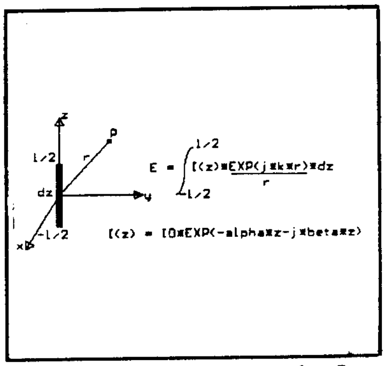

Figure 19 Radiation diagram formulation of a dipole

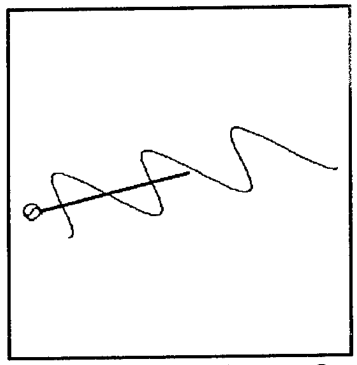

Figure 20 An example of the polarization of wave : rectilinear polarization

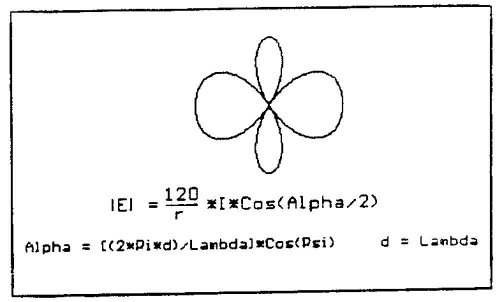

Figure 21 Radiation diagram in polar coordinates

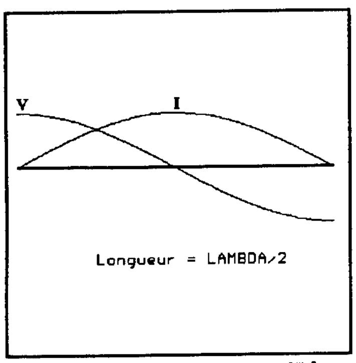

Figure 22 The shape of current and voltage along a resonant antenna

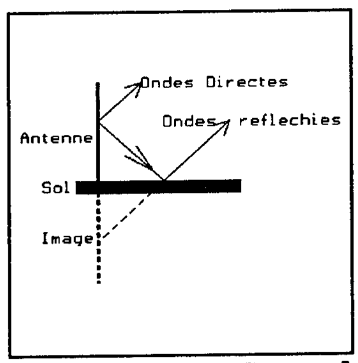

Figure 23 Ground effect

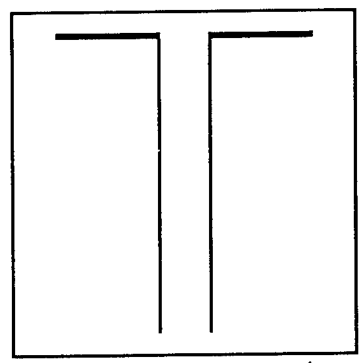

Figure 24 Two wire supply

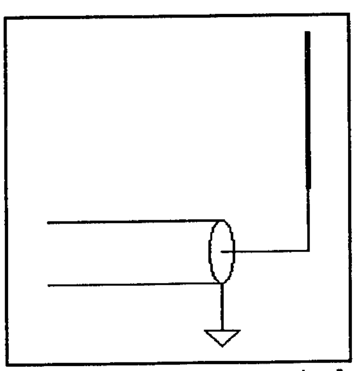

Figure 25 Coaxial line supply

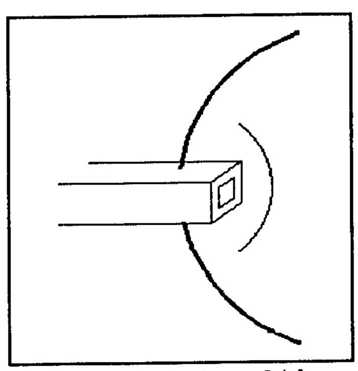

Figure 26 Other forms of supply

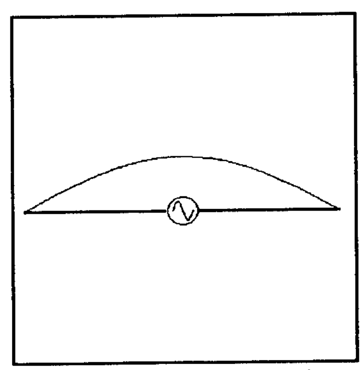

Figure 27 Center sound supply of an antenna

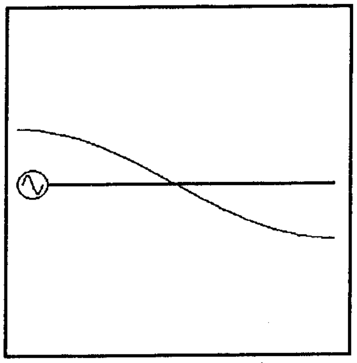

Figure 28 Extreme end sound supply of an antenna

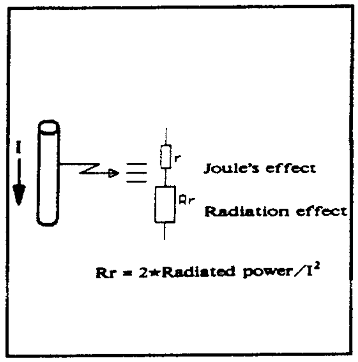

Figure 29 Antenna resistance

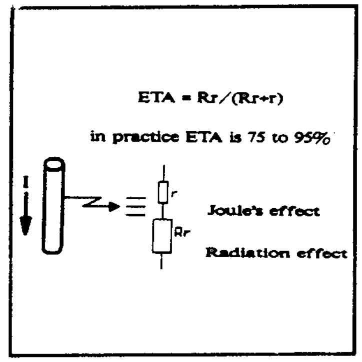

Figure 30 Efficiency of an antenna

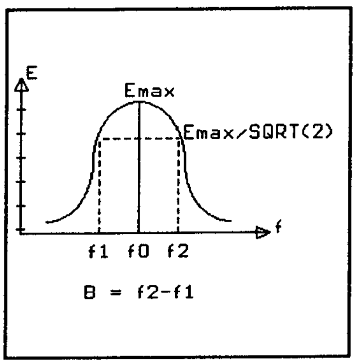

Figure 31 The band width

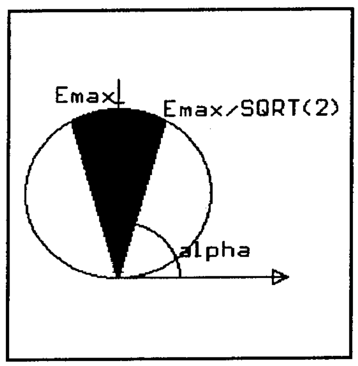

Figure 32 Beam width

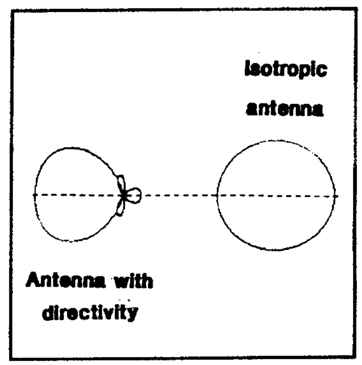

Figure 33 Antenna directivity

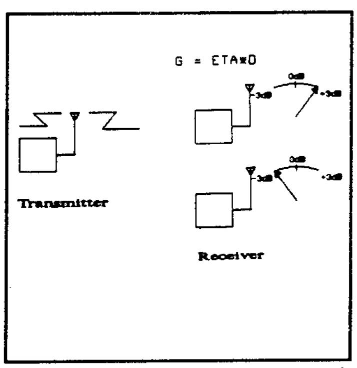

Figure 34 Radiated power

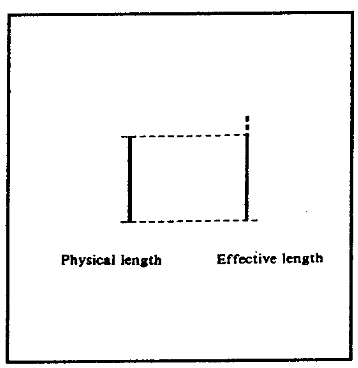

Figure 35 Effective length

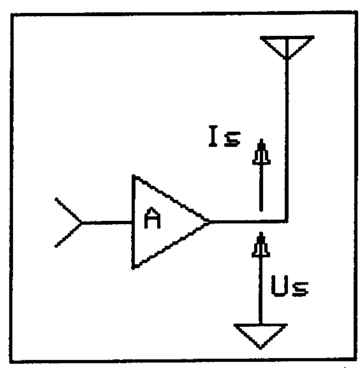

Figure 36 Apparent power radiated

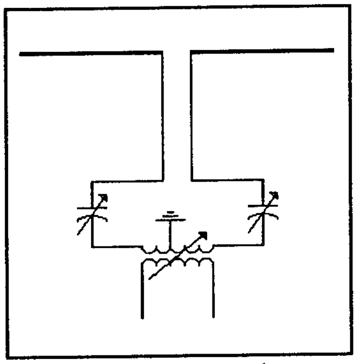

Figure 37 Antenna matching

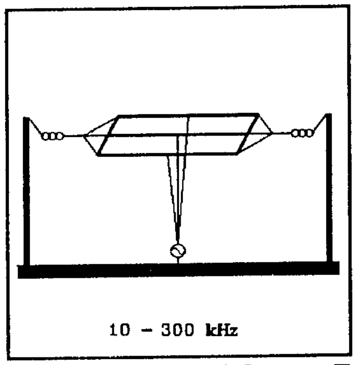

Figure 38 T antenna

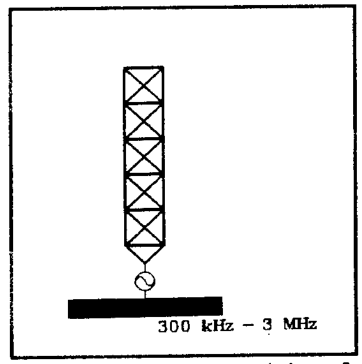

Figure 39 Vertical antenna

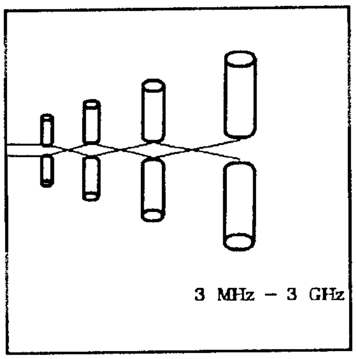

Figure 40 Log-periodic antenna

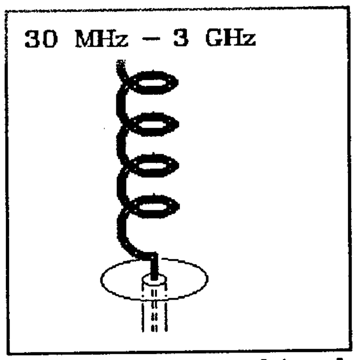

Figure 41 Helical antenna

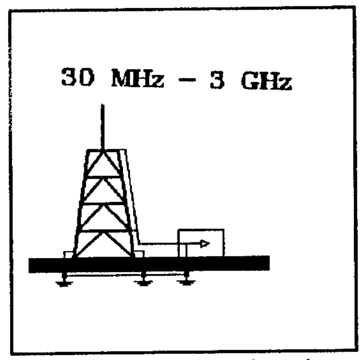

Figure 42 Quater wave vertical antenna

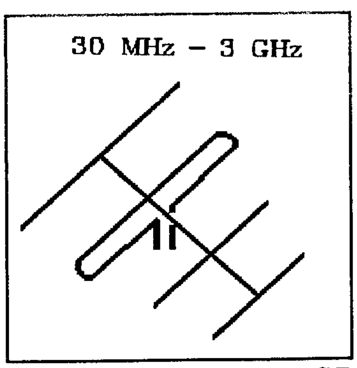

Figure 43 YAGI antenna

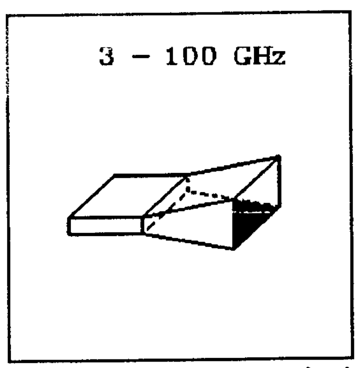

Figure 44 Pyramidal horn

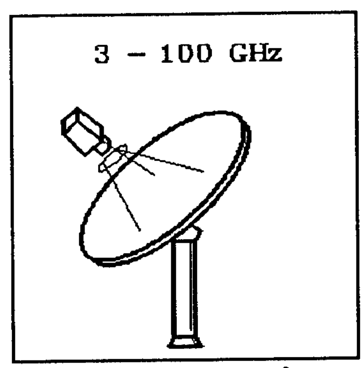

Figure 45 Parabolic reflector with center feed horn

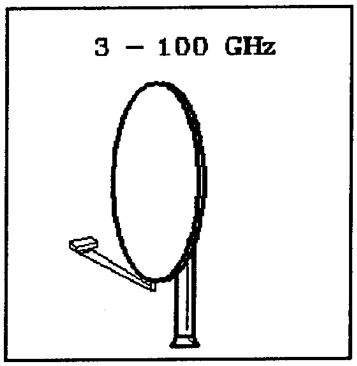

Figure 46 Parabolic reflector with deported feed horn

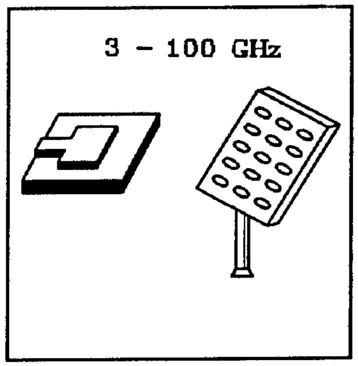

Figure 47 Microstrip antenna

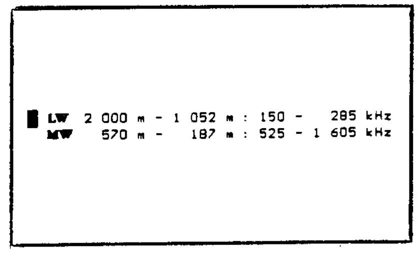

Figure 48 frequency ranges of radio-broadcast bands

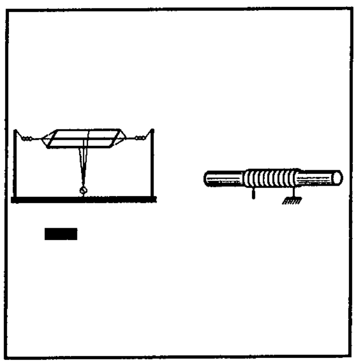

Figure 49 Radio-broadcast band types of antenna

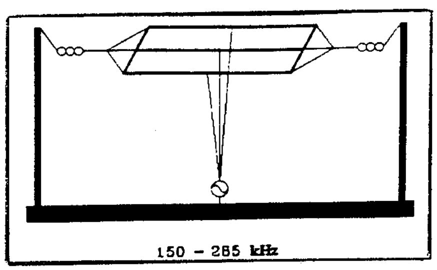

Figure 50 Choice of a radio-boadcast band antenna

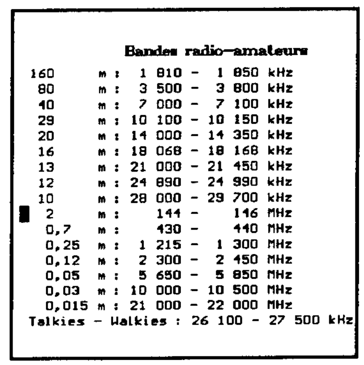

Figure 51 Frequency ranges in the radio-amateur band

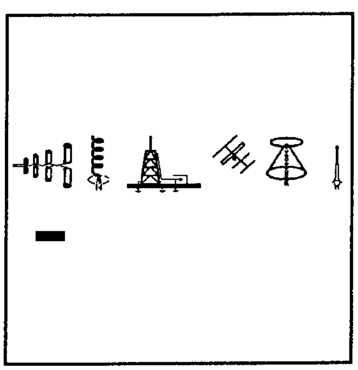

Figure 52 Radio-amateur band types of antenna

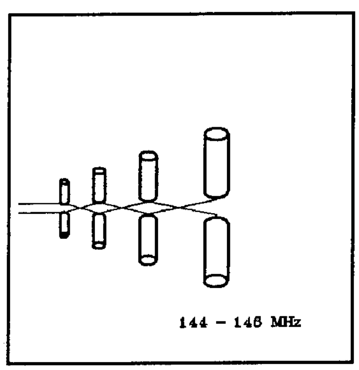

Figure 53 Choice of radio-amateurs band antenna

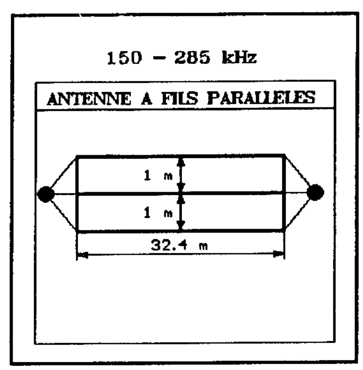

Figure 54 Design of a radio broadcast band antenna

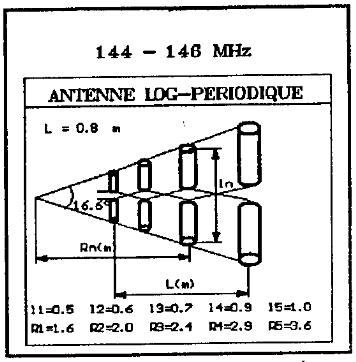

Figure 55 Design of a radio-amateur band antenna

Frequency bandwidth :	150 - 285 kHz
Wavelength :	1 379.0000 meter(s)
Radiation resistance :	0.1239 Ohm(s)
Radiation power :	1.6525 watt(s)
Directivity :	1.5000

Figure 56 Parameters of a T antenna

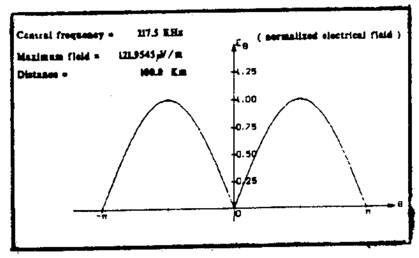

Figure 57 T antenna radiation diagram in cartesian coordinates 2D

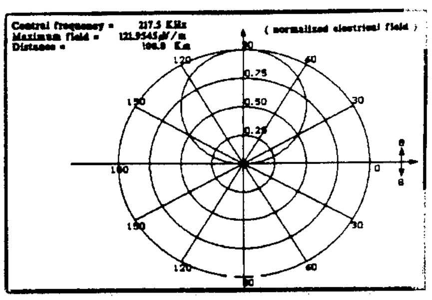

Figure 58 T antenna radiation diagram in polar coordinates

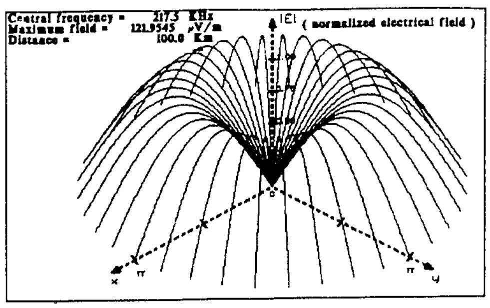

Figure 59 T antenna radiation diagram in cartesian coordinates 3D

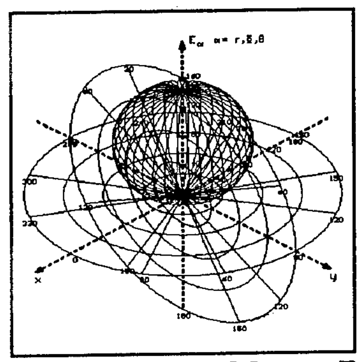

Figure 60 T antenna radiation diagram in spherical coordinates

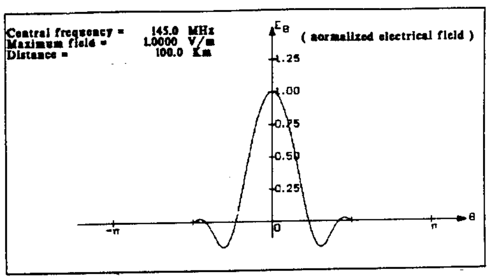

Figure 61 Helical antenna radiation diagram in cartesian coordinates

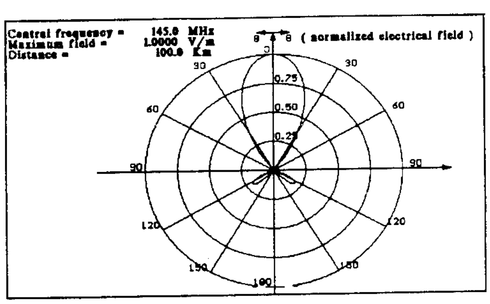

Figure 62 Helical antenna radiation diagram in polar coordinates

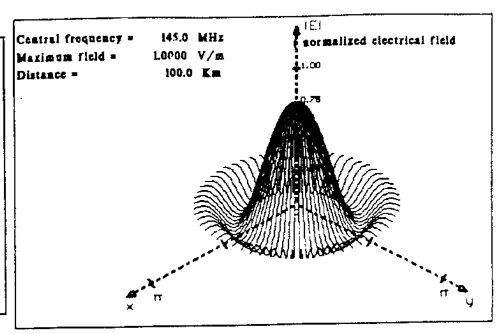

Figure 63 Helical antenna radiation diagram in cartesian coordinates

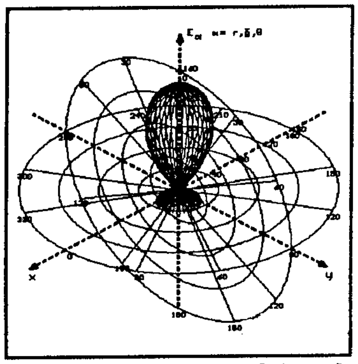

Figure 64 Helical antenna radiation diagram in spherical coordinates

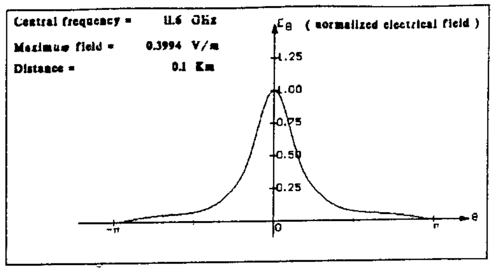

Figure 65 Pyramidal horn radiation diagram in cartesian coordinates 2D

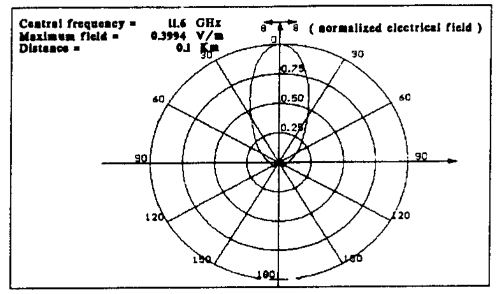

Figure 66 Pyramidal horn radiation diagram in polar coordinates

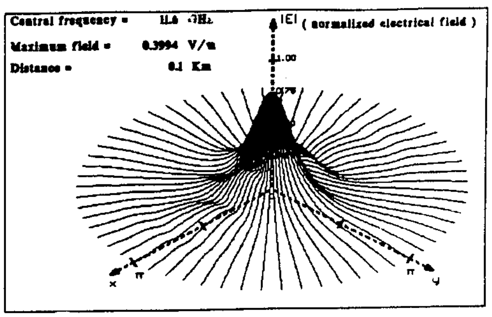

Figure 67 Pyramidal horn radiation diagram in cartesian coordinates 3D

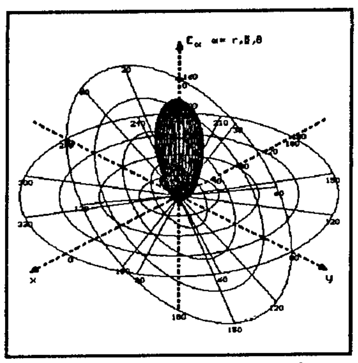

Figure 68 Pyramidal horn radiation diagram in spherical coordinates

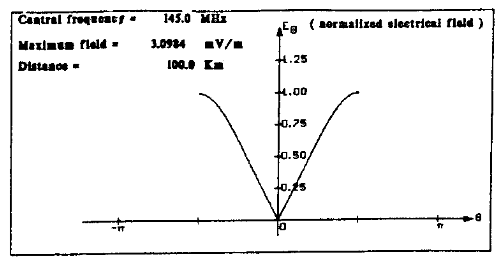

Figure 69 Quarter wavelength antenna radiation diagram in cartesian coordinates 2D

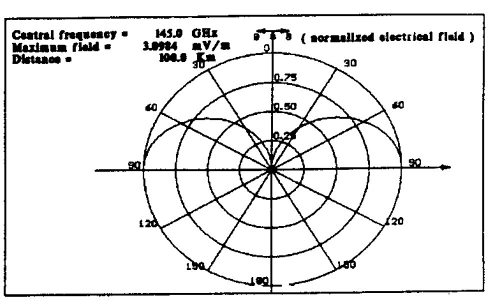

Figure 70 Quarter wavelength vertical antenna radiation diagram in polar coordinates

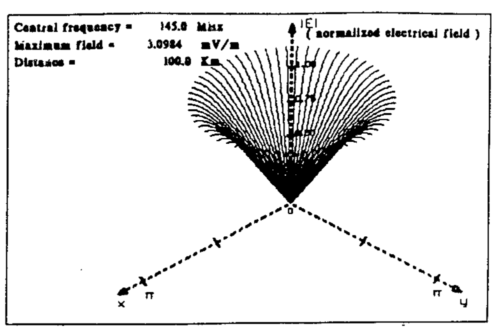

Figure 71 Quarter wavelength antenna radiation diagram in cartesian coordinates 3D

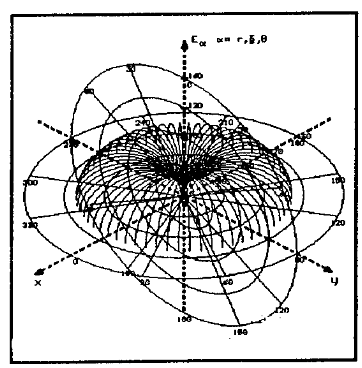

Figure 72 Quarter wavelength antenna radiation diagram in spherical coordinates

Teaching Computational Electromagnetics at Northeastern University: From PCs to Supercomputers

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Abstract

As supercomputers become more accessible and as inexpensive personal computers become more powerful, the numerical modeling of electromagnetic fields in non-idealized geometries becomes increasingly practical. To enable graduate students to solve useful real-world problems, Northeastern University's course ECE 3347: *Computational Methods of Electromagnetics* teaches the important techniques of field and wave simulation, making use of a variety of programming languages, graphics packages, and computer systems which range from home computers to the most powerful supercomputers. Strong emphasis on algorithm design and computer testing helped motivate students to develop an understanding of the major issues involved in using computers to simulate electromagnetics problems.

Introduction: Computational EM at Northeastern University

Electromagnetics is a major research area in the Electrical and Computer Engineering Department at Northeastern University in Boston Massachusetts. The department consists of about 50 faculty and 100 full-time graduate students, and maintains the second largest funded research budget in New England. The Center for Electromagnetics Research is an NSF Industry/University Center of Excellence which is the focus of much of the EM graduate research at the university.

Although the computational electromagnetics course ECE 3347 has been offered for some time, it has only been during the 1991-92 academic year that instruction and assignments on supercomputers have become part of the academic curriculum. Both the massively-parallel Thinking Machines CM-2 and the Cray Y-MP platforms were used in computation problem sets. With the increasing interest in solving large, practical EM propagation and

This work supported in part by the Pittsburgh Supercomputer Center under Coursework Grant TRA920076P

scattering problems – many of which cannot be solved without resorting to numerical computation methods – students' familiarity with state-of-the-art supercomputing is becoming essential.

Many of the graduate classes are taught in studio classrooms and broadcast to local area industrial sites as part of the Network Northeastern Program, or across the United States as part of the National Technological University. The studio classroom offers the option of using both a board and an overhead camera. Conventional blackboard lecture presentation is often supplemented with multi-color video displays from texts, journal papers, and presentation graphics.

It has been observed that students taking the course find it enjoyable and interesting, and quite useful for their own research. As such they worked very hard, commenting in evaluation forms that the work load was much greater than other classes, but that it was worth the effort.

NU Course ECE 3347: Computational Methods of Electromagnetics

The syllabus for the Winter 1992 quarter of ECE 3347 is shown in Figure 1. The topics covered include standard EM computational methods, such as Moment Methods, but also more modern techniques: FDTD, conjugate gradient methods, stimulated over-relaxation (SOR), and multi-step Lax-Wendroff methods, to name a few. This syllabus is similar to that of other universities, in particular, one reported by Iskander [1]. The prerequisites for the course include graduate electromagnetic field theory and mathematics, as well as a fair amount of programming experience.

The major complaint of the 17 students who took ECE 3347 was the lack of a unified textbook specifically dealing with *electromagnetic* numerical computation. *Numerical Recipes*, by Press, et. al. [2] is an excellent all-round reference, and Lapidus and Pinder [3] is useful for pure mathematical theory, but no book deals with both finite methods and moment methods for electromagnetics. This problem has been recently alleviated with the publishing of several new texts [4,5].

Two important aspects of ECE 3347 are the development of scientific computing expertise and the understanding of engineering design in numerical electromagnetics. Half the student's grade is based on a term project of his or her own choosing. The project was not intended to represent original research, but rather more of an independent replication of results published in the literature. One-third of the projects did involve original research, which may be incorporated into the students' ongoing theses. Five problem sets determine the remaining 50% of the grade: three computational assignments and two assignments which derive mathematical bases for several methods.

Although all students were offered accounts on the university's VAX 6420 mainframe, most used computers they were already working with. These included Sun 3 and Sparc 440 workstations, Macintosh IIsi and IBM compatible 80286, 80386, and 80486 desktops, and a Convex 210 computer. Arrangements were also made through the NSF- and NIH-sponsored Pittsburgh Supercomputer Center for computer time on their CM-2 and Cray Y-MP supercomputers as part of their Educational Coursework Grant program. One major point observed in teaching the class is that to be useful in general research, the numerical methods must be transportable to a wide variety of computational platforms.

Allowing students to use any computer they felt comfortable with, along with their favorite high-level programming language and graphics software, provides flexibility and avoids the steep initial learning curve accompanying learning a new programming language. No software, except for the SAS-Graphics package [6], was made available to the students. Everything used for simulation was completely written by each student for his/her own computer system. For some students, the first few weeks were somewhat aggravating, but most were constructing their first iterative Laplace's Equation solver by the second lecture.

The most popular programming language was MATLAB, and FORTRAN was the compiled language of choice. However, software was also written in Mathematica, HP-Basic, Pascal and C. Separate graphics packages included: SAS-Graphics, BBN RS-1, Trimetrix Axum, Microsoft Excel, Autocad, and Lotus 123. One lecture was devoted to teaching CM-FORTRAN, and one student independently (and successfully) learned C*, so students could program that massively parallel Single Instruction Multiple Data CM-2 computer. The single 100 minute lecture certainly could not develop fluency with a new language, but it was enough to establish an appreciation of parallel architecture and programming.

Each of the students who chose to use the CM-2 to solve matrix equation problems using the conjugate gradient method got the correct answer and demonstrated a 1 to 2 order of magnitude performance improvement over conventional computers. Several subtle lessons were learned in working with the supercomputer. First, although FORTRAN is considered by many computer scientists to be antiquated and inefficient, it is the language of choice for scientific computing, both with the massively parallel CM-2 and the powerful Cray Y-MP. The more modern C programming language is supported on the CM-2, but because of its unique hardware/compiler architecture, floating point calculations can only be performed 1/32 times as often as with CM-FORTRAN. A second lesson is that computer performance comparisons can be misleading. For example, students found that it takes about the same amount of time to invert a 100 by 100 double precision element dense matrix on a conventional computer or the CM-2 using the conjugate gradient method, or using a 80486 desktop using MATLAB. However, to invert a 1000 by 1000 matrix takes roughly the same amount of time as for the smaller case on the CM-2, 40 times longer on a VAX and so long on the desktop (because of repetitive data swapping to disk) that it could not be measured.

One problem set in ECE 3347 is based on one-dimensional FDTD modeling of reflection from a lossy dielectric half-space. Issues such as the Courant number, differentiability of the incidence pulse (Gaussian versus truncated sinusoid), loss behavior in the time domain,

and absorbing boundary conditions were examined. Many students were surprised when they specified the electric field pulse with zero magnetic field, and watched as two waves—a left as well as a right propagating wave—were generated. An example of graphical output, showing a single Gaussian electric field pulse, computed using the FDTD algorithm, as a function space and time approaching and reflecting off the boundary at $SPACE = 491$; and also attenuating into the lossy medium with a different velocity (as seen by the space/time slope) is shown in Figure 2. The effect of not using an absorbing boundary on the left lattice termination is clearly exhibited with another reflection. The time domain analysis and display is instructive since although the wave pulse propagates, reflects, and attenuates as one might expect, the usual reflection and transmission coefficients are formulated in the frequency domain, making the mathematics of a Gaussian pulse interaction quite complicated.

An electrostatic computer problem uses iterative relaxation methods to solve for the total potential between and surrounding a pair of capacitor plates. The electric field lines must also be displayed. This non-trivial plotting task is accomplished by using analytic function theory to find the stream function orthogonal to the potential function, and then realizing that the electric field lines coincide with its level contours. Students also are exposed to boundary effects from the lattice termination in this problem.

The final computational exercise, offered as an alternative to the conjugate gradient problem, is to solve for the currents on a variety of dipole antennas using the Method of Moments.

Reading the term papers for ECE 3347 was informative and satisfying. Some of the more original project titles are: "Novel Absorbing Boundary Conditions", "Moment Methods in Polygonal Wire Antennas", "Electroquasistatic Solution of Laplace's Equations for a Field Emission Microtip Structure" which was later used as part of a Master's thesis on vacuum microelectronic device design (with equi-potential contours around a field emitter shown in Figure 3), "Scattering from Inhomogeneous Dielectric Cylinders Using the Unimoment Method", "The Numerical Solution of the Time-Dependent Schroedinger Equation" (with a sample interaction of a wave with a square potential well clearly displayed in Figure 4), and "U.S. Coast Guard WHEC 378 Hamilton Class Cutter High Frequency Antenna Model" (which makes use of the Numerical Electromagnetics Code EFIE and MFIE simulation). The typical term paper was 35 pages long and was of sufficient quality to be considered a professional technical report.

Conclusions

It appears that ECE 3347 has been an important part of the graduate electromagnetics education at Northeastern University. Many students use the methods learned in their current research to simulate effects with detail that is otherwise impossible. The areas

of student research aided by this knowledge range from microwave magnetics to quantum physics, and antenna design to microelectronics.

Teaching students Connection Machine FORTRAN was less difficult than was expected. Once the parallel architecture is discussed, highlighting the major new constructs and syntactic differences in the context of a particular problem gives the students enough to have them experiment and program efficiently.

The design-oriented format of the class was found to be a strong motivating force. The appeal of using software to perform real-world engineering analysis and application design is universal among the students. The students perceived the computer problems as an engineering challenge, and gave high priority to solving them. In addition, the practical aspect code writing, with emphasis on the engineering problem solution rather than the finer points of the code, is good preparation for future electrical engineering work.

Exposing students to many computational platforms helps illustrate the nature of available resources. By encouraging students to discuss the benefits and disadvantages of one system over another among themselves lets them come to their own conclusions about the best approaches to computational problem solving.

Acknowledgements

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NORTHEASTERN UNIVERSITY

ECE–3347 Computational Methods in Electromagnetics

Winter 1992

INSTRUCTOR:	Prof. Carey Rappaport 235 Forsyth Building Work phone (617) 437–2043
OFFICE HOURS:	Tuesday 1:00–3:00 and Thursday 1:00–3:00 or by appointment
CLASS TIME:	Monday and Wednesday 9:50–11:30. (EST)
TEXT:	**Required:** Lapidus, L. and Pinder, G., *Numerical Solution of Partial Differential Equations in Science and Engineering*, Wiley, 1982. **Suggested:** Hall, C.A. and Porsching, T.A, *Numerical Analysis of Partial Differential Equations*, Prentice Hall, 1990. Press, W.H., et. al., *Numerical Recipes*, Cambridge, 1986. Harrington, R., *Field Computation by Moment Methods.* **Recommended (on reserve):** Hoole, R., *Computer Aided Analysis of EM Devices.* Burnet, *Finite Element Analysis.* Strikwerda, *Finite Difference Schemes and PDE's.* Segerlind, *Appl. Finite Element Analysis.*
GRADING:	Homework (3 two-week and 2 one-week assignments): 50% Term Paper: 50%
OBJECTIVES:	To develop an understanding and appreciation of the approximations, mechanisms, and mathematics of numerical computation, with emphasis in electromagnetics. Using rigorous and complete development of topics starting from first principles, the course will provide the student with the background to attack and solve complex problems which cannot be solved using standard modal or ray optics methods.

SYLLABUS

Topic 1 7 lectures	**Finite Differences.** Introduction to difference approximations of continuous functions: one dimensional integration, first order ODE's, Laplace's equation, wave equation, non-uniform grids, FDFD/FDTD.
Topic 2 3 lectures	**Matrix Manipulation.** Technique for working with large matrices: review of LU decomposition and Gaussian reduction, sparse matrix techniques, the conjugate gradient method.
Topic 3 4 lectures	**Finite Elements.** Variational theory of finite elements, element specification and connectivity, spurious modes.
Topic 4 3 lectures	**Moment Methods.** Specialization of finite elements to Galerkin and other moment methods for solving antenna and waveguide problems in terms of the impedance matrix.
Topic 5 2 lectures	**Radiation Boundary Conditions.** Approaches to terminating the computational boundary for exterior (radiation) problems.

Figure 1: Syllabus for ECE 3347

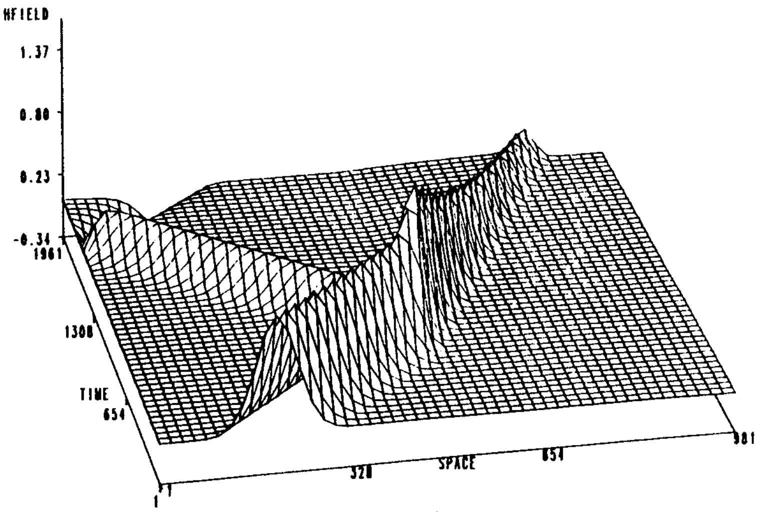

Figure 2: Problem set 3 solutions: FDTD analysis of a Gaussian electric field pulse reflecting off, and transmitting into a lossy dielectric half-space, $\epsilon = 4\epsilon_0$, $\sigma = \frac{1}{50\eta_0 \Delta\tau}$, $\Delta\tau = c\Delta t = .5$.

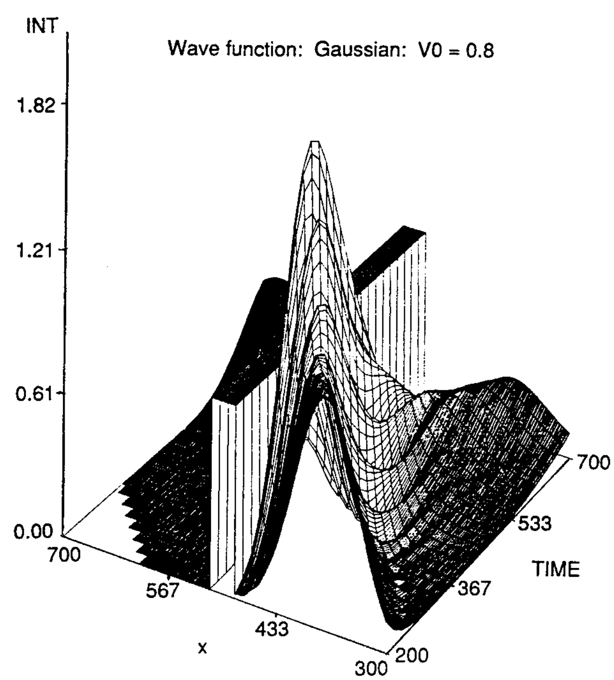

Figure 3: Equi-potential contours around the emitter tip of a vacuum microelectronic amplifier model.

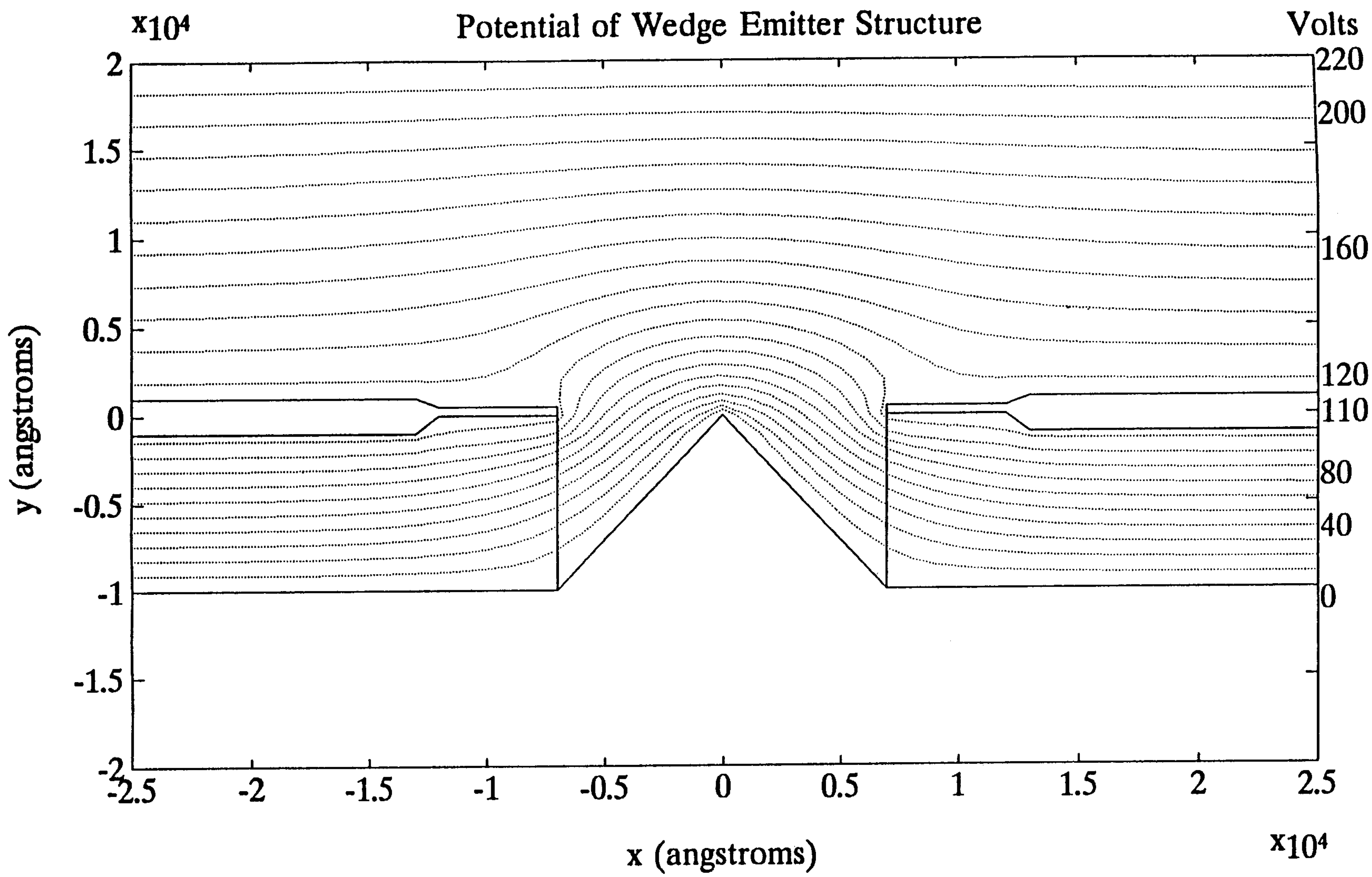

Figure 4: A Gaussian wave packet incident on a potential barrier of fixed width and small height.

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